

Mechanical Design and Prototyping of a Neonatal Incubator for
Areas with Intermittent Electrical Grid Power

by

Elaina Kim Present

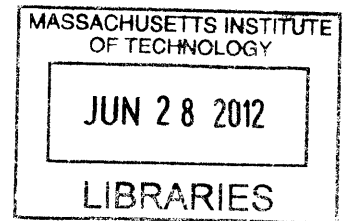
Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Mechanical Engineering

at the

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ARCHIVES



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ABSTRACT

Every year, 1.1 million infants die from complications related to preterm birth. An estimated 80% of these deaths could be prevented through the use of non-intensive methods, including thermal regulation. Neonatal incubators are common life-preserving devices for preterm infants in developed countries, but are under-utilized in much of the developing world due to designs intended for large hospital settings their need for constant electrical grid power and. A design is here proposed for a portable off-grid neonatal incubator for use in those areas. The design is honed through human-centered design practices and the use of SolidWorks representations. Early-stage prototypes are constructed from foam and ABS. Prototyping in ABS required overcoming difficulties presented by the size constraints imposed by the thermoforming machines available in the Laboratory for Manufacturing and Productivity.

**Thesis Supervisor: Sanjay Sarma
Title: Professor of Mechanical Engineering**

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INTRODUCTION

The Problem

There are 15 million children born prematurely every year, between 28 and 37 weeks gestation. Complications related to preterm birth lead to the death of 1.1 million of these children – more than 3,000 a day⁽⁷⁾. Over 80% of these deaths occur due to lack of non-intensive care, such as warmth or feeding support⁽⁶⁾.

Humans in general are quite good at regulating their own body temperatures. When skin sensors indicate the body is too warm, sweat works via evaporation to cool it down. When the sensors indicate the body is too cool, shivering warms it. Infants, however, cannot shiver, and so rely on less efficient, oxygen-intensive fat-oxidation processes to keep their body temperatures up. However, premature infants have a much more difficult time generating heat and regulating their own body temperature than full-term infants, because much of the development necessary for this process does not begin until 32 weeks' gestation⁽³⁾. Children born before that time have effectively no way to heat themselves, rendering common insulation-based methods of warming such as blankets and clothing fruitless. Those children born between 32 and 37 weeks gestation have thermal regulatory systems that are functioning beneath critical capacity. All premature infants, therefore, need heat provided from an external source⁽⁴⁾.

Neonatal incubators were developed in the early 20th century to provide heat to children born prematurely⁽⁵⁾. By the mid-1940s, incubator use was common practice in hospitals in the United States and United Kingdom⁽⁶⁾. However, seventy years later, incubators are still not a universal option because of their high price tag, dependence on reliable electricity, and need for technical support and skilled operation. Portability poses another problem: 50% of all premature children are born at home worldwide, but transport incubators are large contraptions designed with wheels intended for hospital hallways, well-maintained roads, and professionally-staffed ambulances. Lack of reliable electric grids is another significant issue, since incubators require constant electrical power to maintain a life-sustaining thermal environment.

These impediments to incubator usage contribute to an unequal survival rate for premature infants across geographic regions. For instance, South Asia and sub-Saharan Africa account for nearly two-thirds of premature births, and three-quarters of worldwide deaths due to preterm birth complications⁽⁶⁾. The health workers and clinics that serve this region need an option better suited to their operational environment: an incubator that is affordable, portable, and operates through glitches or blackouts in the electric grid.

The Project

In order to improve the current situation, a new, portable, grid-independent incubator is being developed using phase change material as the method of heating. It was begun under the name Anya by a team of designers including Subhrangshu Datta and Chitro Neogy, both alumni of MIT. Before the involvement of any members of the MIT mechanical engineering department, they had developed both a very clear picture of the need for the product and a clear working concept⁽¹⁾. Anya is currently owned by FrontierMed Technologies.

Anya was intended to be usable anywhere – a home, a health clinic, or in transit from one to the other. In order to achieve this, it was designed to have two distinct units: the incubator unit and a docking station. The incubator unit, similar in size to a portable infant car seat, could be brought by a birth attendant to preterm births, or by a health worker to a home where a preterm birth had occurred.

The incubator consists of a portable, heated, closed bassinet with simple monitors for temperature and heartbeat. It has no electric plug, but instead uses a pack of carefully selected phase change material to maintain its temperature. The pack of phase change material can be heated by immersion in boiling water until it forms a liquid. It is then placed back into its slot in the incubator unit, where it maintains a relatively constant temperature as it freezes to a solid over the course of two or more hours. When the child is removed from the incubator for feeding, the pack of phase change material can be re-melted by re-immersion in boiling water.

The incubator unit has straps and handles, making it easy to transport by whatever means are used locally. Thus family members can bring the child in the incubator to a hospital or

health clinic themselves if necessary without further specialized medical transport. Whether by foot, train, rickshaw, shared van, motorbike, or any other type of transportation, they can be assured that the child remains at a stable, life-preserving temperature. The attribute of boiling water as the intended heat source greatly enhances this transportability, as it is a common heat source – it can be found or created in any home around the world, and is widely available at tea shops or food stands should a trip take more than two hours.

The second unit of the system, the docking station, will be kept at hospitals and health clinics. Unlike most current incubators, it has no stand or wheels, but sits atop a table. It has an electronic interface that connects to the incubator unit and interfaces with an Android smart device system so that health workers can easily monitor multiple infants simultaneously. It also has an electric plug, making unnecessary the use of boiling water as a primary heating mechanism when grid electricity is available.

Subhrangshu Datta and Chitro Neogy commissioned a cosmetic prototype of one design of this concept, which is shown in Figure 1 in various configurations. Figures 1a and 1c show size- and weight-accurate 2.5 and 4 lb preemie dolls in the closed incubator unit. Figure 1b shows the back side of the unit, where the phase change material compartment is located. Figure 1d does not include the lid, and the metal plate separating the doll from the phase change heating material can be seen. Figure 1e shows an empty incubator unit in a docking station form.

Datta and Neogy brought the cosmetic prototype to small hospitals in India and solicited feedback. I did not become involved with this project until well after their return, when MIT Professor Sanjay Sarma gathered three undergraduate students to further the goals of the project in an academic setting. Stephanie Whalen's SB Thesis of this year, *Nonelectric, Standalone Heating Element for an Infant Incubator* details the heat transfer modeling of the device as well as the search for a phase change material of suitable price and physical properties. The monitoring and Android portions of the project were pursued as an Undergraduate Research Opportunities Program (UROP) project by Delian Asparouhov. My SB Thesis focuses on the mechanical aspects of the design.



(a)



(b)



(c)



(d)



(e)

Figure 1: FrontierMed Technologies' Cosmetic Anya Prototype, Photographs

The idea of using phase change material as a backup to electric grid power for an incubator has been suggested before⁽²⁾. However, none of those involved with this project are aware of any transport-friendly incubator making use of a phase change material heating system, or any incubator that uses phase change material as its primary method of temperature maintenance.

METRICS OF SUCCESS

Goals for this project were determined at the outset by both industry and academic personnel. As the project continued, goals were readjusted to focus on academic value. Emphasis was placed throughout on the creation of a product that is safe, reliable, low-cost, attractive, and easily manufacturable near where it will be used.

In the design process, a broad range of criteria for success are considered. The entire system design focuses on the health of the child, prioritizing it as the foremost consideration. That single focus indicates many necessary attributes. Operation must be possible and intuitive for operators with little or no training. The unit must be easily cleaned and sanitized to reduce the chance of transmitting infections to a child with a weak immune system. The temperature of the incubator unit must be maintained, while ensuring ventilation and air circulation to aid the child's breathing and reduce the risk of SIDS.

Beyond these absolutely essential criteria, there are many secondary considerations to allow the product to function up to its potential in every environment in which it is designed to operate. The incubator unit must be easy for family members to travel with, regardless of form of transportation, including on foot. The infant must be held securely to reduce the impulse of a family member to open the covered bassinet and restrain it manually. Indicators, as well as the child, must be easy to see at all times, both by family members and by healthcare workers at the clinic. The heating device must be able to be exchanged without disturbing the infant. The interface between the incubator unit, the docking station, and the Android platform must be seamless and intuitive. All this must be achieved in a lightweight and cost-efficient device, with a target weight of under 5 kg and cost of \$150 at scale production⁽¹⁾.

Many of these necessary attributes had begun to be addressed in the cosmetic prototype that was brought to India, but many had not yet been discovered. Work was required on every front.

DESIGN

The Incubator Unit

By redesigning the incubator unit using the same original concept and incorporating the feedback received during its tour of India, I was able to make significant improvements in all of the design criteria. As shown in Figure 1, the design used for the cosmetic prototype had the overall shape of a modified cylinder lying on its side, with flat handles waterjetted from sheet metal on the ends and a flattened bottom. Approximately two thirds of the cylindrical top was made of clear plastic, allowing visual monitoring of the infant, while the remaining third was opaque and stored the phase change material heating element. The phase change material heating element was stored in the same compartment as the child, accessible only by opening the entire top, and separated from the child by a slotted metal barrier. The ends, supporting the handles, were opaque plastic. The base piece was supported only by its own plastic – the handles were separate, self-contained units on each end. Plastic-covered foam filled the base and formed a hollow suitable for a specific size of child, with an elastic band of approximately two inches in width providing securement.

This design was compact, lightweight, and attractive, but had significant potential for improvement. The placement of the heating element within easy reach of the infant posed a risk for contact burns, as shown in Figure 1d, in which a size and weight accurate doll representing a 4.5 lb prematurely-born infant is in direct contact with the metal plate separating it from the phase change material. This placement also had the potential to create temperature gradients in the incubator, did not provide any means of encouraging airflow, and reduced the child's already cramped quarters. The lightly padded sheet metal handles threatened to cut into the hands of the family member carrying it as the padding became worn. The ability to see into the carrier was limited, as shown in Figure 1b. In addition to these prospective design shortcomings, there were many aspects of the design

and performance that were not thoroughly considered, including the mechanical reliability of plastic in the developing world and the method of heat introduction to the system in cases when grid electricity was available. I attempted to address these issues in my redesign.

The redesigned incubator unit (Figure 2) consists of an upper and a lower plastic portion (hood and base), each manufacturable using vacuum forming or other thermoforming processes, including blowmolding, a process which is common in many developing countries for use in making plastic soda bottles. The plastic base has protruding feet as part of the same unit. The feet are punched out after thermoforming, allowing for the threading of the handles (see Figure 3), and for the drainage of any small amounts of liquid that may come into the unit as a residue from washing or by other means.

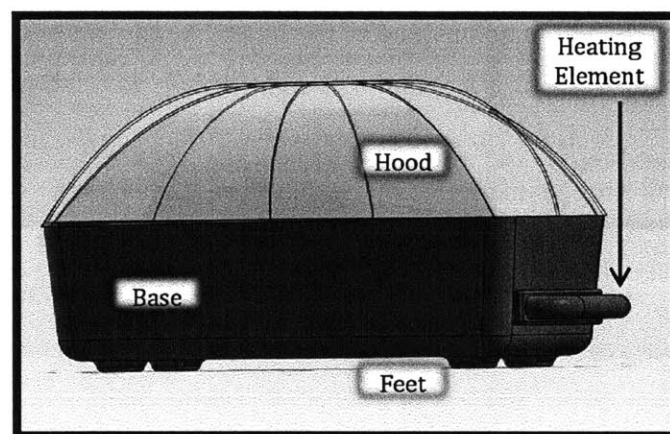


Figure 2: Incubator Unit, Side View, SolidWorks

The outer tangent dimensions of the redesigned carrier are 12"x12"x22". These dimensions are consistent with feedback received in India, where it was observed that the original design was well suited for very premature infants but did not accommodate the full range of children it was intended to serve. Figures 1a, 1c, and 1d show the original cosmetic prototype incubator unit first with a 2 lb micro-preemie realistic doll, then with a 4.5 lb premature realistic doll.

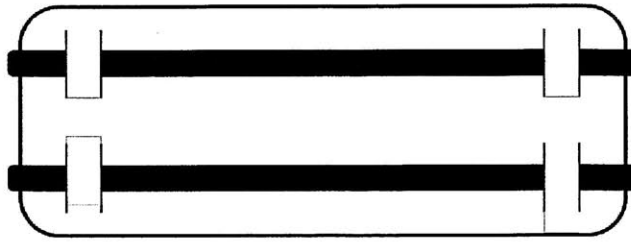


Figure 3: Bottom View of Incubator, Showing Threading of Straps, Sketch

Inside the base, there are several layers of material. On the bottom is a complete layer of thermally-insulating foam, above that, a U-shaped piece of the same material. A cross section of the interior of the base is shown in Figure 4. The redesigned phase change material heating element consists of a tray with phase change material heating packs, which is inserted through a hole on one end of the base. The tray has a shape that complements the U-shaped foam, but is half its height. Above the U-shaped foam, an inch beneath the top of the base, is a nylon mesh that is the surface for the infant. This construction with insulating foam on five of the six sides of the heating element increases the fraction of heat that goes towards warming the infant. The design also allows the heating element to be removed for re-melting in boiling water or exchanged for a second heating element without disturbing the child or opening the warmed top chamber to ambient air. By suspending the infant a small distance above the heating element rather than placing the two next to one another, the possibility of surface burns being sustained is greatly reduced. Such placement also greatly helps the circulation of the air in the unit, as the less dense hot air naturally rises, thereby helping to heat the entire volume to a consistent temperature while increasing air circulation, which reduces the risk of SIDS.

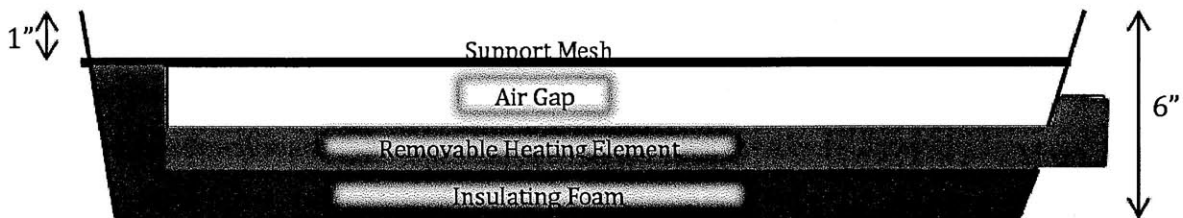


Figure 4: Layers Inside the Incubator Base

The redesigned hood is a domed shape rather than the partial cylinder of the earlier version. Replacing the half-cylinder arch-style top with a domed shape allows the child to be seen from anywhere in the room and accommodates a wider variety of clinic setups, allowing a supervisory eye to be more easily kept on the child at all times. The cut sheet-metal handles are replaced by a single 1.5” wide nylon strap that threads through the hollowed feet on the bottom and retainer clasps on the ends of the base, then snaps to itself, creating a complete loop. Two lengths of strap travel the entire length of the incubator unit, distributing the load on the plastic and increasing the mechanical safety of the unit. The heating element is kept securely in place during transport by the tension from the strap. The nylon handles represent an improvement over the previous metal handles because they are lightweight, secure, washable, ergonomic, and do not interfere with tending to the infant or exchanging the heating element.

Table 1: Incubator Unit Design Criteria and Proposed Solutions

Incubator Unit Design Criteria	Proposed Solution
Consistent Temperature Throughout Top Chamber	Heating Element Beneath Top Chamber
Easy to Carry	Redesigned Handles
Child Visible from Any Angle	Domed Hood Heating Element Beneath Top Chamber
Washable	Modular Plastic, Nylon, and Coated Foam Construction
Change Heating Element without Disturbing Child	Heating Element Beneath Top Chamber
Air Circulation	Heating Element Beneath Top Chamber
Liquid Drainage	Hollow Feet
Reinforcement for Plastic Base	Nylon Straps Beneath Plastic Base
Sized for Range of Infants	Dimensions Expanded to 22”x12”x12”
Hot Surfaces Don’t Contact Child	Heating Element Beneath Top Chamber
Manufacturable	Designed to be Thermoformable
Efficient Use of Heating Element	Heating Element Surrounded by Insulating Foam

The Docking Station

The docking station of the cosmetic prototype was at an even earlier stage of the design process than the incubator unit. It consisted solely of a single shaped piece of foam, approximately in the shape of an extruded L. The long base of the L was grooved to allow the incubator unit to rest securely upon it, while the trunk of the L rose above the incubator unit, allowing the display to be visible when the portable unit was docked. Figure 1e shows the cosmetic prototype incubator unit docked in the matched docking station. There were plans to use the docking station to electrically maintain the temperature of the incubator unit, but these were not fully developed.

Though aesthetically pleasing, this portion of the design required further development. The docking station design severely limited the angles at which either the infant or the monitor readouts could be seen. It was optimized for a specific clinic layout, in which multiple incubators would be placed end to end, and monitor displays were only needed from limited angles. The intended ability to use electric grid power, when available, to heat the incubator unit was not fully thought out, and the proposal of introducing electricity into an economically manufactured environment that had seen some use with an infant raised some concern.

The first revision I made to the design was to forgo the use of electricity to heat the incubator unit itself, instead using electricity in the docking station to prepare a spare phase change material heating element to be exchanged with the one in the incubator unit as necessary. This has the additional benefit of making the exchange of a solidified heating element for a melted one a normal part of incubator operation, whether grid electricity is available or not, and creates a built-in temperature check cycle.

The second issue I sought to address was the lack of visibility of both the infant and the monitor readouts. Figure 5a shows a sketch of an early plan, in which a single vertical pole with a display rose above the incubator unit for at-a-glance updates and the dock for the smart device was at platform level. Though an improvement, new concerns developed that a large docked tablet smart device could block access to the infant, and that significant loss

of aesthetic value had occurred. These concerns led to further redesigns to the design shown in Figures 5b, 6, and 7.

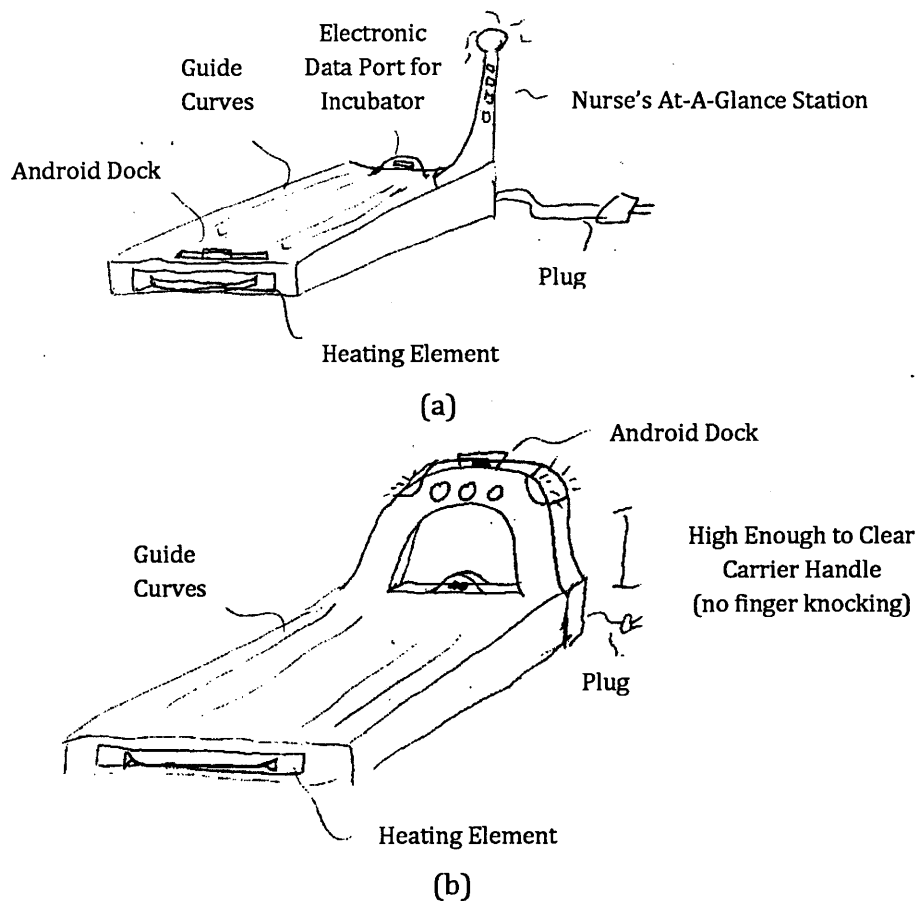


Figure 5: Docking Station, Sketch

The redesigned docking station consists of a large plastic base with guide track grooves and two vertical plastic loops. The feet of the incubator unit are designed to fit into the guide tracks so that, when the unit is pushed backwards, the uncapped electronics port will align with the electronics input port on the lower vertical loop of the docking station. The port for the smart device is on the upper vertical loop of the docking station, visible above the closed incubator unit from any angle from which the screen of the device can be read. Sensor-integrated lights on the upper corners of the upper vertical loop can be seen from anywhere in the room.

This docking station provides no risk of electric shock for the infant, as the method of temperature control of the incubator unit is identical to the method when the unit is used

independently of the docking station. The combination of the domed top and hollowed smart device dock allow the infant to be seen from any angle of the room, and to be accessed from any side, increasing the ability of the docking station to adapt to any hospital or health clinic environment.

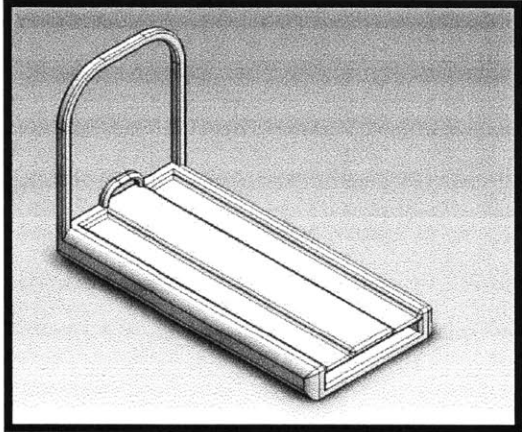


Figure 6: Docking Station, ISO, SolidWorks

In addition to electrically heating a spare phase change material heating element when grid power is available, the redesigned docking station is designed to allow easy monitoring of the infant, or of several infants, through direct visual means as well as integration with an Android smart device.

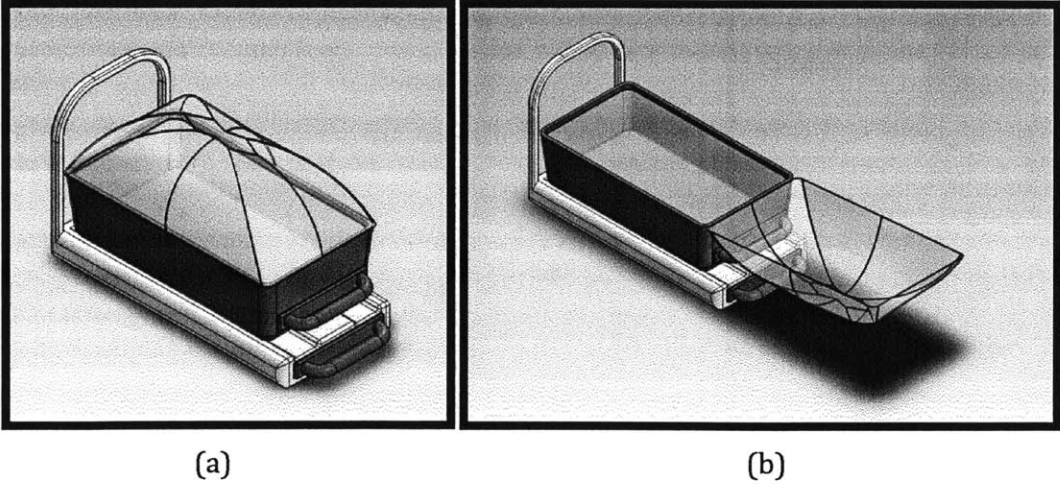


Figure 7: Docking Station with Incubator Unit, ISO, SolidWorks

PROTOTYPE

Creating useful prototypes of the size and approximate materials desired for this project proved to be a significant challenge. Sources are detailed for any materials in this section that proved troublesome to acquire, to aid in the work of any future student pursuing similar projects.

Demo Baby

It was important to obtain a size- and weight-accurate doll for testing purposes. The system is designed to be used with infants of a range of sizes, from the smallest viable human up through sickly children of normal birth size and weight. Birth weight dolls are somewhat expensive, though generally available, but dolls of accurate size and weight for premature infants are difficult to find. Eventually, dolls representative of infants born at two different premature gestations, a 4.5 lb “preemie” and 2 lb “micro-preemie” were purchased through the Web Store of the BabyWearing Institute in Utah for reasonable prices. These dolls are visible in Figures 1a, 1c, and 1d.

Foam Model

A foam model was constructed to provide a full size 3-D visualization of the redesign. Materials used were ¼” foam board, DOW blue foam buoyance billets, masking tape, duct tape, and cotton string. The foam board was purchased from Artist Supply near Central Square. The blue foam was acquired from Dick Fenner in the Pappallardo Laboratory, though is also available from various marine supply stores in the Boston area.

The foam board was used to represent the plastic portions of the carrier. Because foam board does not easily make curves, a truncated pyramid was used to represent the domed hood. The blue foam was used to represent the interchangeable phase change material heating element insert and the high thermal resistance foam padding. The heating element is shown in the model incubator unit in Figures 8a and 8c, and beside it in Figure 8b. Figure 8d does not include the insert. The blue foam was cut using the hot-wire cutter in

the Product Design Lab (MIT room 35-452) run by Professor David Wallace. Duct tape was used to represent the feet as well as to hold all blue foam parts together. String was used to represent the nylon strap. Masking tape held all foam board portions together, and acted as the hinges.

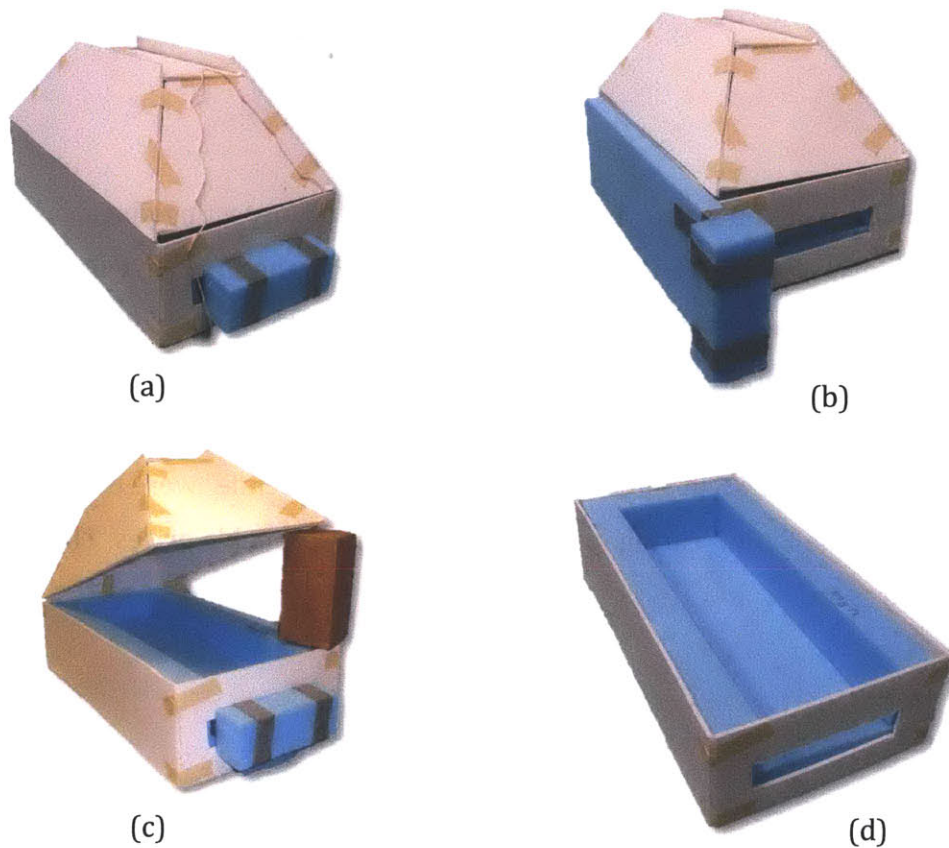


Figure 8: Foam Model, Photographs

ABS Model

Challenges

Following the completion and approval of the foam model, the next logical step is the construction of a looks-like, works-like model: a model made of similar materials and of similar shape and feel as the final is intended to be, but made by different means. This is an

old concept but often more difficult to carry out with modern manufacturing methods because of the high cost of tooling. Plastic in particular is generally shaped by being heated either to melting point, in the case of molding, or to a malleable state under the melting point, in the case of thermoplastic that can be shaped by forming. Both molding and forming require the use of a negative of the desired result. Naturally, plastic can also be machined by more traditional subtractive processes such as cutting and turning; these do not pose tooling challenges as regularly.

For the first round of plastic prototyping, the base of the incubator could be satisfactorily modeled by a rectangular box made of plastic sheet. The upper, curved, portion, however, presented a challenge to manufacture within the laboratories available to the undergraduate mechanical engineering community. The top choice was to use blow molding, the process used to make PET soda bottles, and the process intended to be used for the final product's on-location manufacturing in India. However, blow molding was not readily available at MIT, so other methods were considered.

A process similar to blow molding is thermoforming or drape forming, in which thermoplastics are heated to temperatures at which they become malleable, and then draped over a negative, or mold. In some cases, called vacuum forming, air is drawn through small holes in the negative to help the plastic conform more completely to the mold; in others, gravity alone draws the plastic onto the mold. The Laboratory for Manufacturing and Productivity at MIT has two thermoforming machines, a 430V CAM Thermo Former, and a Formech 660 Vacuum Forming Machine. Though the two have slightly different configurations, they both work on the same basic principle: flat plastic stock is placed in an oven-like environment and heated, then removed from the heat. The mold is raised on an actuated platform and pushed into the malleable plastic, with a vacuum system available to provide suctioning and a better fit. Unfortunately, neither of these machines is equipped to deal with parts 22" in length. The former is limited by heating elements covering an area of approximately 18" x 18". The latter has a set of interchangeable frames as its limiting factor. These frames support the plastic stock during the heating process while the negative is in a repository below; once the material is malleable, the heating elements are removed and the negative brought up through the

frame, forming the plastic. The largest frame available was 17" x 17". These difficulties initially ruled out drape forming.

Added to the challenge of finding a machine capable of doing the forming was the challenge of finding or creating a negative for use as a mold. An accurate domed shape was beyond the means of the project at this stage and so the goal became to build a half-cylinder hood similar to the one that had been on the original cosmetic prototype. This separated the challenges posed by size and shape and allowed work towards viable options for forming oversize plastic sheeting at MIT to be continued without the added cost or time delay inherent in an overly complex shape.

The goal inner diameter for the half-cylinder was set at 11.5". Suggestions included everything from using five-gallon buckets as molds, which was ruled out because of the taper, to buying a large PVC pipe, cutting it in half, and using that for the hood, which was ruled out due to cost. Using PETG plastic, which could be bent into shape and held under tension, was also considered. Eventually a 12" diameter, 0.1" thickness cardboard tube intended for cement work was procured from Home Depot. The material used to do the forming was 1/8" ABS. ABS is the same thermoplastic provided with the 2.007 laboratory kit. The first attempted approach was to try heating the material in the oven of the CAM Thermo Former and then transferring it quickly to the cardboard tube. The CAM Thermo Former was chosen because both Dave Dow and I were more familiar with it than with the Formech 660, and because it allowed for direct numeric control of oven temperature.

First Forming Attempt

A piece of 24" x 24" 1/8" ABS stock with a line drawn down its middle was placed in the oven of the CAM Thermo Former. Both upper and lower oven temperatures were set to 375°F. The stock was not cut down to its intended final size of 22" x 19.85" because of the possibility of the stock thinning or stretching in the forming process. The mechanical shear at the Laboratory for Manufacturing and Productivity (LMP) has a configuration that would allow for trimming the ends after forming. To aid alignment, a line was also drawn down the cardboard tube, using a square. The tube was prepared on a small pallet inverted on a

cart, as close to the oven as possible, and coated lightly in baby powder to prevent the plastic from sticking. The stock was periodically rotated in the oven to minimize the time any one portion spent out of the direct influence of the heating element.

After well over fifteen minutes, the stock was displaying signs of malleability and was removed and draped on the cardboard tube. The stock readily formed a curved shape, but no degree of accuracy proved possible: uneven fixturing and inadequate heating element size had left the piece unevenly heated. The edges that had last been rotated out of the heat were only very slightly malleable, and the piece hardened quickly into a lumpy, unevenly curved surface. Using a heat gun over the course of the next hour, small portions were brought up again to a temperature of malleability, but greater conformation to the desired shape was not achieved as each localized section was prevented from conforming to the mold by the rigidity of the rest of the piece. Weights were attached to the bottom of the stock, but no noticeable shape change occurred. Figure 9 shows the intended hood piece on the cardboard tube at the conclusion of the first forming attempt.



Figure 9: ABS Hood, First Forming Attempt, Photograph

Second Forming Attempt

A second attempt at forming the top piece was made several days later with a fresh piece of stock, many lessons learned, and a better understanding of the factors at play. The major shortage of the first attempt had been the uneven heating, so a decision was made to try the Formech 660 with the largest frame, which had the potential to provide uniform heating at

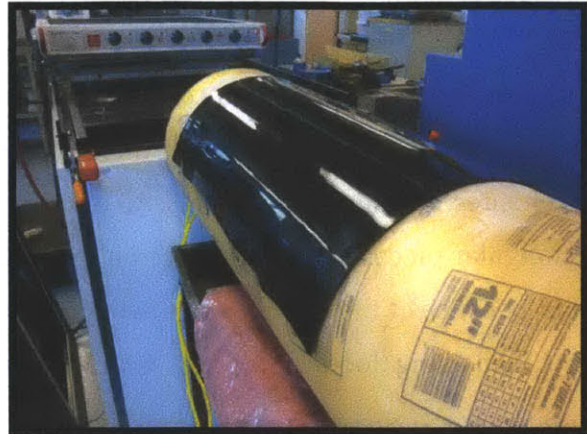
the cost of direct temperature control. The Formech 660 has a single overhead heating panel of 27" x 29.5", as well as fixturing for larger set ups (up to 16") than the CAM Thermo Former. The Formech 660's larger heating panel allowed the entire piece of stock to be heated at the same time. The 24" x 24" ABS stock was cut down to its desired final size of 22" x 19.85" on a band saw. Because the lower repository was not being used for the negative, steel plates were placed down on top of the frame, creating a flat surface capable of containing the sheet of ABS and preventing the stock from drooping down into the space where the negative would normally be. Aluminum strips were folded into Ls and placed near each corner to enable the heated piece to be picked up by people wearing gloves.

As stated above, the Formech 660 does not have direct temperature controls or readouts as the CAM Thermo Former does. Instead, it has knobs similar to those typically found on stoves, with unitless markings of one through seven. The heating was begun with the dials around six, but they were soon turned down to three for fear of burning, rather than softening, the ABS stock. The ABS stock formed quickly into an inverted-U arch as the heating elements warmed it from above and the molecules on the top surface expanded while the steel underneath was still slowly warming up. The stock soon collapsed down and began heating more uniformly than had been possible on the CAM Thermo Former. When the stock was not exhibiting the limpness expected and was puckering around the aluminum, the heat-control dials were turned back up past five. The stock soon became limp and tests performed by gently lifting up on the aluminum Ls showed it to be malleable as well. The heating element was then removed, the stock lifted by the corners, aligned with the line drawn on the powdered cardboard tube, and smoothed into place.

Figure 10a shows the Formech 660 with the heating element pushed back and the ABS stock just removed. The steel plates and aluminum Ls are still in place. In Figure 10b, the stock is shown during cooling on the cardboard tube. The edge of the ABS is in contact with the cardboard tube from vertical tangent to vertical tangent, unlike the situation in Figure 9. Slight puckers may be seen at on the bottom edge, a few inches from each end, where the aluminum Ls had been.



(a)



(b)

Figure 10: ABS Hood, Second Forming Attempt, Photographs

As seen in the comparisons in Figures 11 and 12, this second method was much more successful than the first. The ABS took and maintained the shape and curvature of the cardboard tube with very few blemishes. The main aberrations were slight puckerings where the aluminum had been, indicating that consistency of the thermal properties of the surface is critical in this process. The aluminum itself hindered uniform heating.



Figure 11: ABS Hood Comparison, Photograph

Flat Stock Work

With the prototype ABS hood completed, there still remained five plastic pieces to manufacture in order to assemble an ABS incubator unit shell of realistic dimensions: two lower sides, a base, and two ends. All of these were cut out of flat $\frac{1}{4}$ " ABS stock. The three rectangular pieces were cut to size on the band saw using a clamping square guide. The ends, because of the curves, were set up on the Bridgeport TC-3 Mill in the LMP. They were machined using flood coolant, Dave Dow's clamping system, and a $\frac{3}{8}$ " end mill.

These five flat pieces are shown with each of the two hoods in Figure 12, for comparison. The hood from the first forming attempt is shown in Figure 12a, and that from the second forming attempt in Figure 12b. The first hood was not cut down to size, but the inconsistencies of shape are visible nonetheless. The second hood, which was cut down to size before forming, conforms very well to the semi-circular upper portion of the end pieces, but for unclear reasons did not extend all the way to the lower side pieces, leaving a gap. Measurements taken before and after the ABS heat forming show no significant difference in thickness.



Figure 12: ABS Model Comparison, Photographs

Lessons Learned from Completed Prototyping

The only significant design change made after the beginning of the prototyping process was the movement of the location of the hinges on the incubator unit from the side opposite the heating element port to the side with the heating element port. This was done in order to prevent the hood from blocking or physically interfering with the smart device dock set up when the incubator is docked and opened.

This prototyping process led to much more being learned about the prototyping process itself rather than the design, and that knowledge is not without use. A method of forming plastic sheets larger than the technical capacity of the machines in the LMP was constructed with some success, and failed methods were noted and documented. Cardboard was established as a viable mold material, at least for ABS. And the challenge of prototyping full-scale in plastic due to the need for a negative was verified.

NEXT STEPS/SUGGESTIONS FOR FUTURE WORK

There remains a long road ahead of this product before it is ready for market. From a mechanical design perspective, the next key aspect will be material selection. This will be heavily influenced by the thermal needs of the product and the expected stresses and strains, as well as the documented reliability and availability of material choices in proximity to the target markets.

In addition to material selection, a deeper look into fabrication methods is necessary. Forming the hood and base of the incubator unit each as a single piece is the preferred method, so long as sufficient machinery is available. As an immediate next step, I recommend attempting to make a mold for the domed roof out of foam, wood, or a combination of materials. Inexpensive ceramics may be an option. Several hoods can then be formed using the Formech 660 heating element with different materials. If those are successful, a mold of the base should be made as well, with the goal of creating a true looks-like, works like model of the incubator unit.

The design itself still requires further refinement, especially in the areas of fasteners and thermal sealing, as well as in the details of the integration with the monitoring systems and the incorporation of the small power and electronic needs of that quarter.

As the design is honed and mass manufacture concerns come become foremost, attention must be turned to the detailed conditions where mass manufacturing will happen. I have only a rudimentary understanding of the available materials, material quality, and manufacturing capabilities of the geographic regions where this product is intended to ultimately be made. More complete research must be done on this topic, and better approximations of that environment must be used for prototypes at some point in the future, even if that means working off campus.

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