Infant Incubator

F03-Blue Light Therapy Incubators for Neonatal Jaundice in Ghana

Instructor: Dr. William W. Smith

Main Contact: Dr. William Okyere-Frempong

Team Members:

Noah Daugherty

Andres Rodriguez

Elisa Schrader

Alyssa Beyler

Malvika Upadhaya

Table of Contents

Executive Summary

A serious problem in global healthcare is not the lack of existing technology or solutions, but the accessibility to them. This is seen in hospitals in Ghana when treating newborns, especially premature ones, and there is a lack of appropriate equipment to treat them. Currently, babies are transported wrapped in sheets as their caregivers travel to the closest equipped hospital, which can take hours to get to. Dr. Okyere-Frempong has brought this problem to attention and wishes to receive a more secure solution that could help save the lives of these infants.

To aid in solving this problem, a transportable incubator needs to be developed that will provide the necessary life support for the infant and sufficient information to their caregivers, while maintaining manufacturability in Ghana. Project development was initiated by the collection of information that has occurred through various sources such as doctors, nurses and biomedical engineers from the US, Ghana, England, and Colombia. Product developers of other low resource solutions to similar problems from around the world were also included during the research phase. This helped create a comprehensive understanding of the requirements necessary for the final product to be considered a functional incubator. The general requirements are to help the infant maintain their body temperature at an adequate level and monitor their basic vital signs at all times.

The specific medical measurements that should be considered relate to the internal environment of the incubator, which should remain between 28-39 °C, and 40-70% humidity. According to the research, the baby's temperature should be kept between 36.5-37.5 °C. Additionally, the incubator must be able to read the weight of infants between 0.5-4.0 kgs and heart rates between 40-180 beats per minute. The main mechanical requirements include a hood that is sufficiently large to comfortably fit a newborn infant and a structure that is capable of supporting the weight of its components. The main electrical requirements include 140-230 W of heat must be produced inside the incubator, the input of the power supply should be designed for 240VAC 50Hz and the output should be 5-24VDC Additionally, the monitor should be able to display the appropriate information to the caregiver. The materials and manufacturing techniques considered are materials that have the appropriate physical properties and available processes that the potential manufacturer in Ghana has access to.

Various proofs of concept will be performed throughout the process to ensure that all the components perform accurately. First, for mechanical concepts, small versions of the structure will be created and tested for stability and usability. The electrical components and the sensors will be tested against previously accepted devices. For example, to test the accuracy of the

temperature reading, the device could be tested against a mercury thermometer. Additionally, the measurements of the back seat of an average car will be used as a guide for the general size to make sure that the main goal of transportation is met.

Moving forward, the goal is to begin performing these small proofs of concept on individual components of the incubator. This, in addition to receiving feedback from the main advisor, Dr. Smith and the main contact for the project, Dr. Okyere-Frempong, will lead to the definition of the final concept which can then be constructed and tested altogether.

Throughout this entire process, comprehensive documentation will be kept in the form of user manuals, pictures, and an publically available website to ensure that the final product is replicable in Ghana. Additionally, Dr. Okyere-Frempong will learn about the skills used by being actively immersed in the construction phase. The final step of this project is to send this documentation back with Dr. Okyere-Frempong.

Glossary

FDA Ghana: Food Drug Administration in Ghana

IEC: International Electrotechnical Commission

Preterm baby: A baby that is born more than 3 weeks before the baby's estimated due date. Alternatively, it refers to a baby that is born before the 37th week of pregnancy.

Neonate: A newborn baby that is less than 4 weeks/ one month old.

Main Body

1. Introduction and Background

Ghana is ranked within the top 15 African countries with the most newborn deaths[1]. In a study done in the Ashanti Region of Ghana, data from 222 mothers and their babies was collected. The results showed that babies of 115 of the mothers did not survive past their first 28 days of life. The conclusion of the study showed a high level of neonatal death in the Ashanti region which is the most populated in Ghana[2]. This is just a small representation of the infant mortality situation in Ghana and even at a broader scale, in Africa. It is predicted that over a million African babies will die in their first four weeks of life, and the second biggest cause of newborn deaths is preterm birth. Infant incubators are meant to help prevent this by serving the role of a mother's womb when a baby is born preterm or for a full-term baby that is ill.

The main contact for this project is Dr. William Okyere-Frempong who is the founding Medical Superintendent of the Nungua LEKMA Polyclinic, a public health facility in a populous suburb of Accra, Ghana. He has raised the concern of the lack of infant incubators in hospitals such as his own and others in locations that are more remotely located. He has described how, to get a premature baby in need of an incubator to the right location, they are sometimes forced to carry them in their arms in a car for hours to reach the closest hospital with the right resources. The design of an incubator that is affordable and manufacturable in Ghana would allow more premature babies to survive.

When looking at what could be done to help and treat the infants, there is an infinite list of possibilities of features that could be included with any one solution. However, it is necessary to identify the problem that affects the most amount of lives. In this scenario, that problem is the high rate of infant mortality due to the lack of an affordable and locally maintainable device that can provide the basic environment to keep a premature or newborn baby alive.

2. Existing Products, Prior Art

Infant incubators have been around since 1870, when Dr. Stéphane Tarner, an obstetrician, took the idea of chick incubators to develop a box that regulated the temperature of premature babies[4]. Since then, incubators have developed into a device with more intricate features that are capable of regulating the temperature inside the box to keep the baby's temperature at a specific level. In addition to this, they now come with a variety of different features that range from regulating the humidity and oxygen saturation of the incubator environment to keeping record of the baby's weight and incorporating specific lights to treat medical conditions such as jaundice.

The Korle Bu Teaching Hospital, the premier health care facility in Accra, Ghana, is one of the few hospitals with access to the most modern infant incubators in the country. The devices they currently have are from the company Dräger, specifically the Dräger Caleo and the Isolette TI500[5]. The first one being the first incubator to work with continuous monitoring of the baby's temperature. It focuses on insulating the baby and keeping the amount of stress and stimuli to a minimum. The price of the base incubators can range from $3,400 to $5,500 without including the additional accessories such as skin temperature probes, the mattress for the bed, baby positioning aids, tubing grommets, ventilation hose holder, oxygen sensor, water tank, and air filter. On the other hand, the Isolette TI500 is a mobile, intensive care unit that incorporates a double wall structure to reduce the loss of radiant heat while the baby is being transported. The basic pricing of these incubators range between $2,950 to $3,895 without including the additional accessories such as the skin temperature probes, the mattress for the bed, tubing grommets, breathing hose, an air filter , oxygen sensor, restraining straps and a rechargeable battery. The international delivery fees to Ghana and maintenance costs add significant costs.

Due to the high price of basic incubators and the inability to maintain them, some other designs have been created to fit various extreme circumstances. For example, the mOm incubator was developed for refugee camps found in Europe and the conditions in which they live. It is a foldable, inflatable incubator that is designed for easy transport to the refugee camps in the form of a small briefcase and then inflated at the location where it is needed[6]. The main focus of this incubator is to help the baby maintain it's body temperature without the incorporation of humidity. Similarly, a team from Rice University in Houston, Texas developed a laser print incubator, Incubaby, for Malawi and other developing countries. It is an easy to transport incubator made of double wood plywood panels that forms a box where the baby can lay and the temperature can be regulated. The team hopes to keep the production of these incubators between $300 and $400[7].

3. Codes and Standards

There are two main sources of standards that should be considered when developing this product. At the national level in Ghana, there is the Food and Drugs Authority (FDA) Ghana which is responsible for "protecting the public health by ensuring the safety, efficacy, and security of human and veterinary drugs, biological products, and medical devices"[8]. At the international level, there is the International Electrotechnical Commission (IEC), which is in charge of overseeing the regulations of electrical components and their safe usage within other devices. Specifically, for the case of an infant incubator, there is the IEC 60601-2-19 and 60601-2-20 which refer specifically to the safety requirements for static infant incubators and the safety requirements for transport infant incubators, respectively[9]. These standards will be reviewed to understand the factors that play a role in the safety and reliability of the functioning of these devices.

4. Customer Requirements and Engineering Design Specifications

The stakeholder analysis, visualized in **Table 1** and **Figure 1** shows that the most important stakeholders when it comes to design considerations for the device are the nurses, doctors, and manufacturers. The identification of this information is important to direct future conversations, research, and prototypes. To ensure full comprehension of the medical, functional and ergonomic requirements, both doctors and nurses have been contacted. The doctors are the source of the medical and functional knowledge while the nurses, are the main interacting user with the device and are the sources of the ergonomic information.

Stakeholder	Interests	Impact/Effect	Power	Interest
Infants	survival needs	components required to maintain vitals	1	5
Doctors	general infant progression	simple data access	4	4
Nurses	daily infant care	user input / interface	4	5
Technicians	maintenance	component simplicity/lifespan	2	2
Parents	infant survival	visibility and access	2	4
Manufacturer	manufacturing	manufacturability	3	2

Table 1: Stakeholder Analysis This table ranks the relative amount of power and interest of the various stakeholders in relation to their role when interacting with the neonatal incubator.

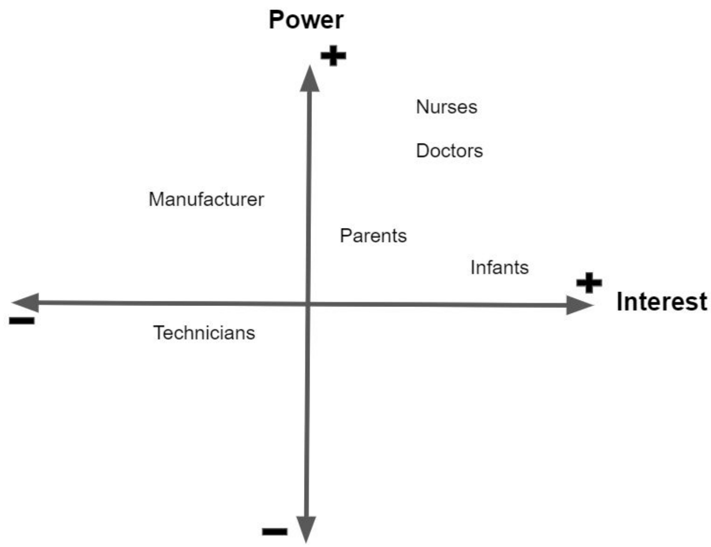


Figure 1: Stakeholder Analysis This graph translates the information from Table 1 and helps visualize which stakeholders are more relevant to take into account when designing the device.

Based on the background research, **Figure 2** divides the major requirements of the development of the incubator into six major categories, and then divides them even further into the corresponding sub-functions. The purpose of this is to organize the various components of the project into the corresponding functional areas.

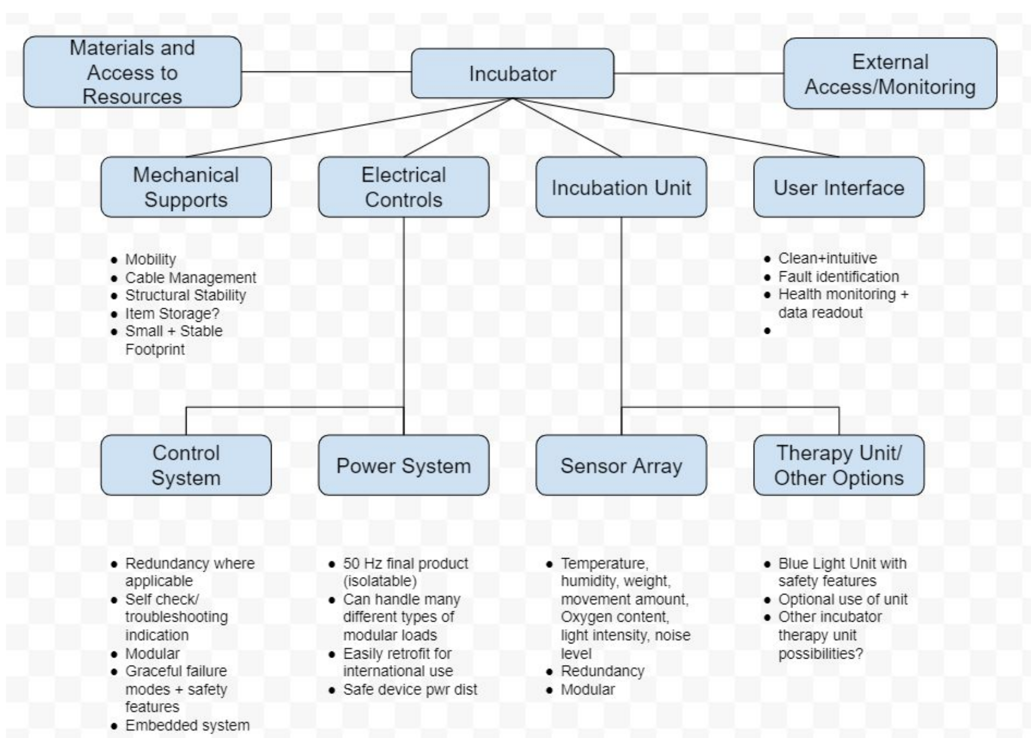


Figure 2: Function Tree The blue boxes are the main functions and the bullets are sub-functions with more detail

The initial, high level customer needs and their corresponding engineering components are simplified in **Table 2** based on the major functional requirements. This analysis helps determine what will be necessary to prove the overall concepts for a functional final product.

Relationships: Strong 5 Medium 3 Weak 1 None Blank	**Engineering Requirements**	materials	energy consumption	manufacturing	consumer testing	strength tests
Customer Needs						
safety		3				5
low cost		5		5		
reliability		1		1		3
energy efficiency (battery)			5			
appearance		1			3	
mobility		1	1	3		
lifespan		5		3		3

Table 2: Form Chart Ranks the correlation between the customer needs on the left side and engineering requirements on the right.

After creating a form chart and combining them with the needs expressed by Dr. Okyere-Frempong, all possible features that the incubator could have are represented in **Table 3.** The purpose of this is to better understand how the medical requirements of the incubator might be impacted on by the conditions in which it will be operating. The scope of the project is defined through this process in terms of taking all the various features found in current, state of the art, incubators, and understanding which ones are absolutely necessary. Those considered to be absolutely necessary and life-supporting are ranked as 1, those that are useful but not entirely life-supporting are ranked as 2, and the features that, although nice ideas, are not needed for this scenario are ranked as 3.

1 - Absolutely Necessary	2- Extras	3- Completely new

- **Sensors**:
  - Temperature
  - Humidity
  - HR
  - O2 Saturation
- **Mechanical Capacity**:
  - Capacity to be on a stand
  - Hand access to baby
- **User interaction**
  - Instructions Manual
  - User interface
  - Calibration system
- **Electrical Requirements**
  - O2 Filter
  - Motor Powered Fan
  - Exhaust Fan
  - General Illumination
	- **Sensors**
	  - Apneia
	  - Weight
	- **Electrical Requirements**
	  - Backup Battery
	  - Interchangeable Power Supply
	  - Redundancy + Maintainable Electrical Components
	- **Mechanical Capacity**
	  - Inclination
	  - Detachable Hood
		- Dual Chamber
		- Heat Cleaning
		- Blue Light Incorporation
		- Cabinet space
		- BP Sensor

Table 3: Ranking of Features The categorization defines the most necessary features (1), beneficial but not life supporting features (2), and add ons that are not required (3).

Finally, the House of Quality seen in **Appendix B** quantifies the features from an engineering standpoint. It takes all the different correlations described before, bringing them together in a comprehensive manner to understand how specific customer needs will be met through the engineering requirements. For example, to be portable, people must be able to lift the device without using a crane. OSHA standards state that any device weighing greater than 23 kg must be lifted by more than one person[10]. Therefore, if the incubator is to be designed to be lifted by two people, the ideal weight should be no greater than 46 kgs when in use.

The numerical values for these requirements are divided into three separate categories: the medical, the mechanical, and the electrical requirements. As observed in **Table 4,** the medical requirements refer mostly to vital signs of the baby inside of the incubator since it is what gives the direct caregiver the specific information about the status of their patient. The incubator must be capable of reading the measurements of the baby's status and communicating those values. These values were identified by speaking to various doctors to understand what the normal range of measurements could be and from there, expand the range that the device will be able to read to cover any extreme circumstances that should be alerted to the caregiver.

Medical Requirements		
Part	**Requirement**	**Specifications**
Shell compartment	**Environment Temp**	**28-39 degrees C**
	Baby temperature	**36.5 < T(baby) < 37.5 C - should be measured in atleast 2 different locations**
	Humidity	**40% - 77%**
	HR	**120 to 160 beats per minute**
	Weight	**0.5 - 4.0 kg**
Blue Light	**Wavelength**	**waveband interval 460 to 490 nm**
	Intensity	**30W/cm/nm**

Table 4: Medical Specification Sheet This lists out the most important vital signs that the incubator needs to keep record of, with specific ranges that it should detect.

The mechanical side of the requirements, seen below in **Table 5,** are all the conditions that the incubator must meet for it to provide the appropriate environment for the treatment of the infant. In other words, they are what allow for the medical requirements to be met in an accurate and trustworthy method without the concern of any external factor. For most incubators, this includes allowing for quick access to the baby and keeping consistent communication with the caregiver about the vital signs of the patient. In the case of this incubator, it must provide a safe environment for the child to be transported to another hospital.

Mechanical Requirements (based off of previous incubators)		
Part	**Requirement**	**Specifications**
Hood	Height	30 cm
	Length	71 cm
	Width	46 cm
	material	nonporous and humidity resistant
Bed (meant to fit the already existing incubator)	weight to support	2.3 kg - 3.2 kg
	width	42 cm
	length	12 cm
	max inclination (degrees)	15 - 30 degrees
	material - mattress	nonporous and humidity resistant
	material - board	nonporous and humidity resistant
Handles	Weight to carry	designed to be carried by 2 people
Base compartment	length	88 cm
	width	46 cm
	height	20 cm
Stand	length	90 cm
	width	48 cm
Access	hand hole diameters	15 cm
	whole side length	67 cm
	whole side width	42 cm
Monitor	length	18 cm
	width	10 cm

Table 5: Mechanical Specification Sheet This table provides the necessary requirements for the main structure and to maintain the environment for the infant.

The electrical requirements are what ensure the safe and reliable operation of the incubator, allowing it to perform the necessary functions and supplement the medical and mechanical operations of the device. These requirements can be found in **Table 6** and they include those necessary for the computer, sensing array, user interface, heating unit, and power supply. As with most incubators, it includes the ability to read the ambient temperature inside the hood, as well as the body temperature, oxygen saturation, heart rate, and weight of the baby. These readings will be outputted to a display, which in conjunction with buttons to control the heating unit, illumination, and alarms to provide warnings to the caregiver, will make up the user interface of the incubator. One requirement specific to this incubator is that due to the target country, Ghana, operating on a different power system than the US, the power supply will have to be compatible with 240V 50Hz Power. The power supply will also need to output enough power to meet the requirements of the computer, sensing array, display, and the heating unit. Given the current design, the heat output required from the heating unit is estimated to be a range from 140W to 230W, shown in section **Appendix B**. This results in an estimated power output requirement of 200W to 300W for the entire incubator.

Electrical Requirements		
Part	**Requirement**	**Specification**
Computer	**Unit**	**Raspberry Pi 4 Model B**
Heating Unit	**Heat Output**	**~ 140W - 230W**
User Interface	**Display**	**Ambient: Temperature and Humidity**
		Patient: Temperature, O2 Sat, Heart Rate, ECG, and Weight
		Machine Status: Battery Level, Plugged In Status, Warning Symbol for Alarms
	Control	**Buttons to change temperature settings, turn illumination on/off, and acknowledge alarms**
	Alarms	**Warning symbol on display as well as a speaker for audible feedback, with option to acknowledge alarm/warning**
Power Supply	**Input**	**240V 50Hz**
	Output	**5-24 VDC ***
	Power Output	**~ 200W - 300W**
Sensing Array	**Ambient (Hood)**	**Temperature, Humidity (at Exhaust)**
	Baby	**Temperature, O2 Saturation, ECG, HR**
	Electrical Compartment	**Temperature**
	Other	**Baby Weight**
		Apnea

Table 6: Electrical Specification Sheet This table includes all the electrical components for the device to function and read vitals. * Will depend on final component supply requirements. Will likely be 24VDC output with voltage regulators downstream of initial power supply

5. Market Research

Various sources were contacted to gain information to help aim the directive of the project. The multiple sources include: Susan Zachariah, MD is a Ghana Pediatrician Specialist at the Korle-Bu Teaching Hospital in Akora, Theophilus Ofori is a Biomedical Engineer at Korle-Bu Teaching Hospital in Akora, Alfred Selorm Betepe is a manufacturer in Ghana and CEO of Seloart Group, Irma Raquel Tabares, MD is a Pediatrician Neonatologist at PROCAREN UCI-NEONATAL in Caldas, Antioquia, Colombia, James Stubbs, PhD, is a Medical Device Company Executive and Biomedical Engineering professor at Georgia Institute of Technology, Matthew Khoory is a co-founder for mOm Incubators and Matthew H. Merves, MD is an Assistant Professor of Pediatrics Division of Neonatology Emory University School of Medicine.

Dr. Zachariah's top priorities to be considered are: weigh the baby, monitor temperature, clean mode autoclave, light source to illuminate the baby, easy to clean and replace, and a need to work without electricity. A current problem she has noticed is the temperature probe for the child reads incorrectly and sets off unnecessary alarms. Continuing from that, she believes setting specific ranges for each child for the alarms would help reduce alarm fatigue. A factor that makes neonatal incubators hard to maintain is that parts are not easily replaceable.

Mr. Ofori provides insight for design considerations. He believes that the ideal humidity range for an incubator is between 80% and 90%. He also notices a need for backup power and switches to manually control the device because of the power outages that can last up to six hours. He observes that the fan and heating elements break down the most and also that the temperature sensor on the baby is unreliable. For transportation, his top priorities are backup power, oxygen cylinder mount, and humidity as necessary.

Mr. Betepe is a very important source for this project because he will manufacture the product and knows what is available in Ghana and that will influence the parts that are chosen. He has access to vacuum forming, a laser cutter, a metal cutter. Plexiglass, aluminum plates, stainless steel, mild steel, and steel plates are available to get in Ghana.

Dr. Tabares provides her experience with transport incubators and explains how they incorporate some amount of humidity into their incubators but also how not having a good regulation humidity can lead to the creation of an infection inside of the child. In contrast to the heat regulation component of the device, humidity is not an essential part of the functioning of the incubator, rather a nice possibility to have. When using a transport incubator, because it is a temporary situation, the need for humidity is not as important as the heat. In her experience, people will transport the babies in whichever way possible even if it is simply in their arms. For babies that are not as stable, this could be life threatening and she also observes the need for an incubator that is easily transportable.

Dr. Stubbs has experience working on medical devices and suggests that the IEC 60601 documents mentioned above should be considered. Stubbs also advised

regarding best practices while considering material options when designing a medical device.

Khoory works for a company that is in the process of creating a static inflatable incubators for refugee camps. Khoory's mOm incubator company focuses on the core functionality which includes vitals and temperature stability. Humidity is not considered a core function and it has an infection risk. He sees creative ideas used a lot to include humidity factor in an incubator that does not focus on humidity. Transport incubators have different standards than static and his company also uses the 60601 documents as a reference needed. The biggest aspect his company struggles with is meeting the standards and regulations.

Dr. Merves allowed for the observation of the cleaning process of a Drager Isolette 8000 . This helped understand how the air flow and humidity systems are incorporated, and how the bed tray can be repositioned on a pair of t-bars. This visit contributed significantly to the design conception.

The feedback from the sources helps determine the core functions and the preliminary design. Based on the feedback, the incubator will include a weight sensor, temperature control, and a custom alarm system. It will not include a humidity system due to the complications and difficulty in completing this task. Based on the availability of materials and manufacturing processes, the incubator will ideally be manufactured by laser cutting plexiglass and manipulating aluminum plates. These materials and design processes take into account that not all manufacturers will have access to these tools. In these cases a more manual process is also possible.

6. Design Concept Ideation

After collecting the data from the various sources, the conclusions were shared with a group of doctors with similar backgrounds to that of Dr. Okyere-Frempong. With their feedback, a final decision about the features that are to be included in the final product is shown below in **Table 7. Appendix A** uses this list to create a variety of possible design ideas. Various combinations of these sketches in addition to the main cutsomer's feedback will be used to create a final image of the concept design.

1 - Absolutely Necessary	2- Extras	3- Completely new

- Sensors:
  - Temperature
  - Humidity
  - HR
  - O2 Saturation
- Mechanical Capacity:
  - Capacity to be on a stand
  - Hand access to baby
- User interaction
  - Instructions Manual
  - User interface
  - Calibration system
- Electrical Requirements
  - O2 Filter
  - Motor Powered Fan
  - Exhaust Fan
  - General Illumination
	- Electrical Requirements
	  - Backup Battery
	  - Interchangeable Power Supply
	  - Redundancy + Maintainable Electrical Components
	- Mechanical Capacity
	- Sensors
	  - Apneia
	  - Weight
		- Dual Chamber
		- Heat Cleaning
		- Blue Light Incorporation
		- Cabinet space
		- BP Sensor

Table 7: Promised Features This table highlights the features from the original table that was developed with the main contact and highlights what the device will include.

The major challenge of this project is not just to design a new incubator, but to make sure that the materials and techniques necessary to build it are available locally in Ghana. To make sure that this is the case, **Table 8** includes a materials list created from those that are used in existing incubators as well as some additional options. The manufacturer was then consulted on the availability of them where he is. Plexiglass, aluminum, steel, and wood are the best options based on the manufacturer’s ability to obtain them.

Material	Pros	Cons
Resin	-Strong -Usually thermoset and won't change with heat after formed -Most are considered non-toxic once set	-Requires us to create a silicone mold (which would be hard to replicate and maintain) -Would need large quantities(probably mailed in)
Wood	-Easy to acquired -Easy to work with	-Easily damaged by heat or liquid
Plexiglass/acrylic	-Can be ordered in sheets -The material used in some current incubators -Can be glued together or use manual fasteners -Decent thermal and electrical insulator -Impact and water-resistant -Clear -Melting point is 320 F	-Can be expensive -May need to be mailed in
Metal	-Higher-strength -Can be formed/bent	-Can be damaged by oxidation -Can have shaper/dangerous edges
Plastics (Acetal/HDPE/LDPE)	-Can be molded into the base of the incubator chamber	-May be difficult to have the proper shape and size
Polystyrene	-Can it be used to create a model to mold plexiglass around possibly? -Melting point 410F	
Parchment paper	-Can heat plastics up without them sticking to the surface below	

Table 8: Materials List This table compares materials that have been considered for the design of the incubator.

7. Computer and Electrical Modelling

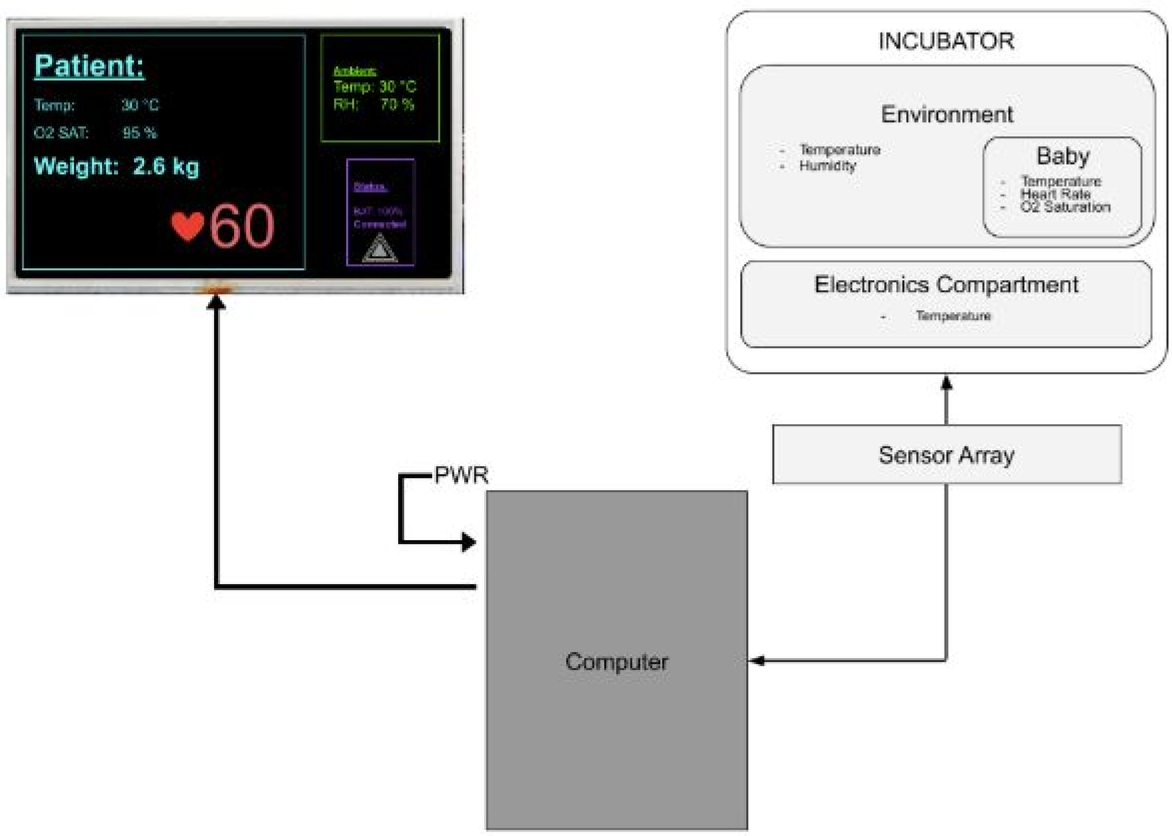


Figure 4: Vitals Monitoring Computer/Electrical System: This Diagram shows the high-level schematic for the vitals monitoring system. It shows the computer taking input from the sensor array and outputting those readings onto the display.

For the electrical control system (viewed above in **Figure 4**), a Raspberry Pi single board computer is being used as the primary control unit. Due to concerns regarding the computer's ability to handle input from all the sensors as well as output to the display and still keep the device modular for future work, a more capable Raspberry Pi 4 Model B is better than the Raspberry Pi Zero. It will handle the input readings from each of the sensors, perform the necessary processing to convert the raw readings into the human-readable data, and output these to a 7 inch display via an HDMI connection.

For sensing, as shown in the figure above, the device will monitor: incubator environment temperature and humidity; temperature, weight, and O2 saturation; as well as the temperature of the electronics enclosure. The incubator environment will be measured from two points, one at the top of the incubator and one at the air exhaust. The point at the top of the incubator will measure only temperature with redundant sensors. The exhaust point will measure both the temperature and humidity of the outgoing air. The humidity sensor will be at the output since they build up contaminants over time, thus it should not be placed inside the incubator.

The sensing of the baby's vitals is arguably the most important part of the overall incubator. It must be monitoring the baby's temperature, heart rate, and O2 saturation. To do this, the sensors will utilize as many open source or standard connectors as possible.

In addition to sensing the ambient environment inside the incubator, the device will also be measuring the ambient temperature of the electronics compartment. This is measured to ensure a safe operating temperature for the components housed inside.

8. Design Computer Modelling

The original concept designs are based on the incubators observed at Emory University Hospital. Concept designs are used to help a client visualize the direction of design. The CAD allows for movement of components in a fashion similar to how they would be expected to in practice. It allows the client to directly critique the concept designs, and the engineers to receive valuable feedback. The first iteration is shown below in **Figure 5.** This feedback is used to generate new ideas and resolve any unforeseen issues. In the first iteration of designs, all mechanical functions described in **Table 7**, are addressed.

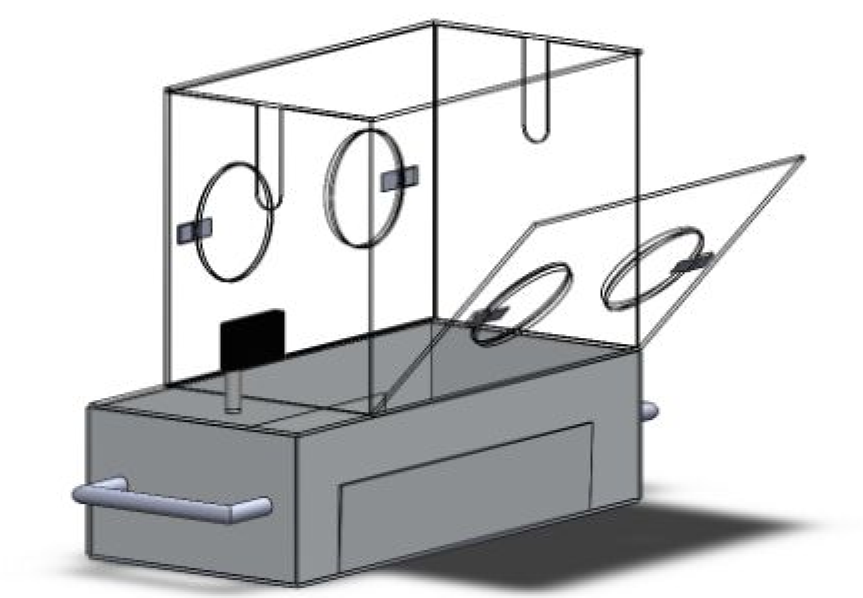


Figure 5: Initial CAD rendering: This figure shows an initial concept design that is based on the incubators that already exist. It will be used as an initial design for prototyping.

9. Summary & Future Work / Project Deliverables

The gantt chart below, **Figure 6,** indicates the tentative schedule for completing the general assigned tasks of the project. It is used to monitor the progress against the expected timeline. As feedback given from various sources is evaluated, the next step is to move onto completing the CAD work, doing the engineering analysis, and prototyping. As progress is made, some of the assigned tasks might move around and the chart will be readjusted.

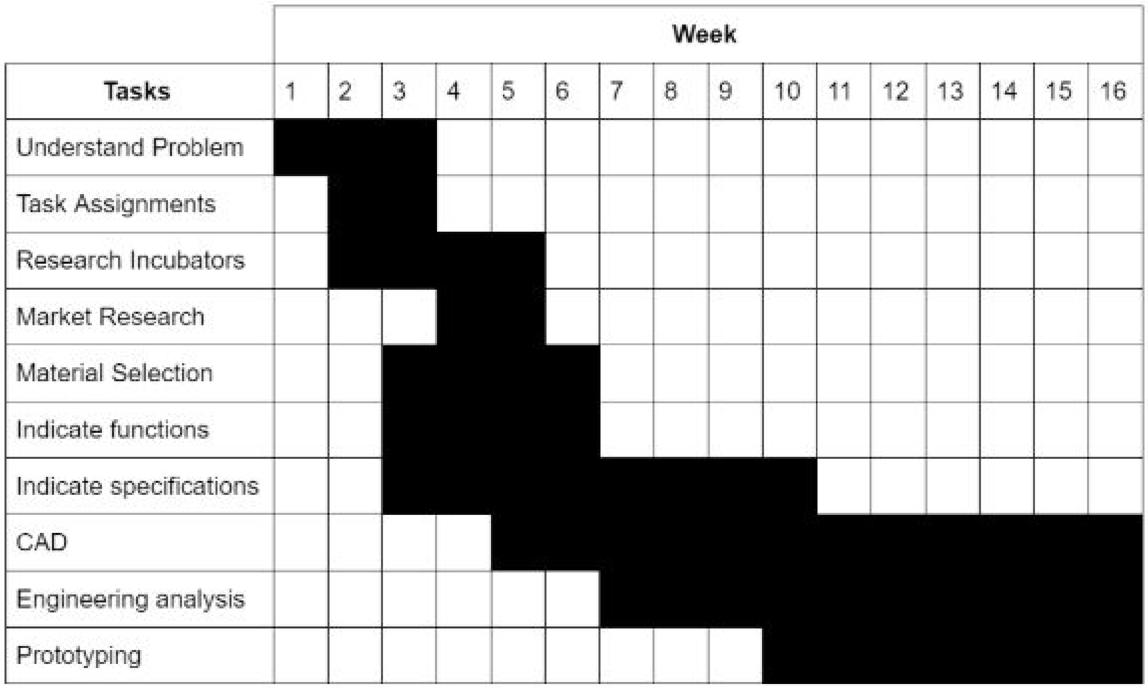


Figure 6: Ganntt Chart: This chart represents the tentative schedule of the project. It will help monitor the status of the progress made and can be be adjusted accordingly.

Moving forward, rapid prototyping of the different concept designs will be done to determine their functionality and further narrow down the final design. Some simplified versions of the structures might be used to do proof of concepts, especially for the various latches and connectors. Once these have been tested and chosen, the final size of the device needs to be determined. The main requirement that has to be met for this is that the incubator must be transportable in the back of an average size automobile. All this together in addition to continuous feedback received from the main advisor, Dr. Smith and Dr. Okyere-Frempong, a final CAD design will be made to review the work. This will allow for the ordering of the final materials and the construction of the main hood component of the incubator.

In parallel, the specific wiring schematics for the sensors, Raspberry Pi and monitor will be created and put together. Various trials will be done to ensure that the measurements are accurately being measured and translated onto the monitor data. The user interface will be tested with various users such as local nurses and doctors and Dr. Okyere-Frempong. Once this is completed, the design of the bottom component of the incubator can be finalized to include the necessary spaces for the electrical/computer components, ventilation and heat systems.

The final materials for this part will then be ordered and the rest of the incubator will be assembled.

Once all the components are put together, the specifications of the incubator will be compared to those that were set in this report to ensure that all the requirements have been met. Dr. Okyere-Frempong will also be thoroughly involved in the manufacturing process to learn the necessary skills needed to do so. Additionally, thorough documentation will be kept to create a set of instruction manuals that will be taken back to Ghana with Dr. Okyere-Frempong, where the final product will actually be constructed. These manuals, in addition to a rigorous amount of images and an publically available website, will be the basis for the replicability of the device which is one of the main components of this project. The final neonatal incubator will be appropriate for travel in an average size vehicle with the main purpose of thermoregulating the infant patient and monitoring all of their basic vital signs. It will be made with the intention of it being manufacturable with the resources available in Ghana.

References

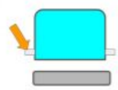
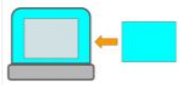
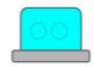
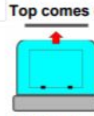
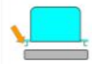
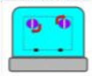
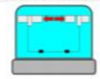
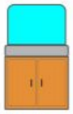
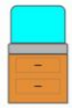
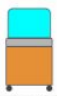
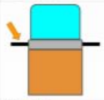
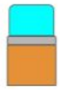
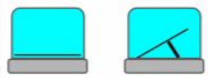
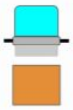
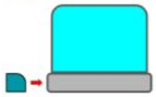
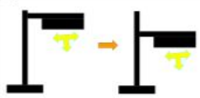
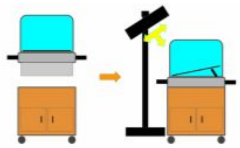
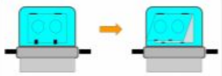
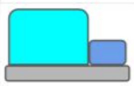
1. Lawn, J., Mongi, P., & Cousens, S. (n.d.). Africa's newborns– counting them and making them count. *World Health Organization*. Retrieved from https://www.who.int/pmnch/media/publications/aonsection_I.pdf
2. Annan, Nancy, G., Asiedu, & Yvonne. (2018, April 29). Predictors of Neonatal Deaths in Ashanti Region of Ghana: A Cross-Sectional Study. Retrieved from https://www.hindawi.com/journals/aph/2018/9020914/
3. DeFrancesco, V. (2004). Neonatal Incubator. Retrieved from https://www.sciencedirect.com/topics/nursing-and-health-professions/neonatal-incubator
4. Blakemore, Erin. "Baby Incubators: From Boardwalk Sideshow to Medical Marvel." *History.com*, A&E Television Networks, 12 Sept. 2018, www.history.com/news/baby-incubators-boardwalk-sideshows-medical-marvels.
5. Accessory Catlogue 2019/2020. (2019). *Accessory Catlogue 2019/2020*. Retrieved from https://www.draeger.com/Library/Content/accessory-ca-9066485-en.pdf
6. mOm Incubators. (n.d.). Retrieved from http://www.momincubators.com/
7. Williams, M. (2015, April 9). Rice device gently warms hypothermic infants. Retrieved from http://news.rice.edu/2015/04/09/rice-device-gently-warms-hypothermic-infants/
8. FDA Ghana. (n.d.). Retrieved from https://fdaghana.gov.gh/
9. IEC - International Electrotechnical Commission. (n.d.). International. Retrieved from https://www.iec.ch/
10. Materials Handling: Heavy Lifting. (n.d.). Retrieved February 19, 2020, from https://www.osha.gov/SLTC/etools/electricalcontractors/materials/heavy.html
11. Llc. (2017, January 2). Heat Loss Double-Pane Window Equation and Calculator. Retrieved from https://www.engineersedge.com/heat_transfer/heat_loss_doublepane_window_13864.htm
12. Engineers Edge, L. L. C. (2017, January 1). Single-Pane Window Heat Loss Equation and Calculator. Retrieved from

https://www.engineersedge.com/heat_transfer/singlepane_window_heat_loss_13863.htm

13. Llc. (2015, February 11). Convective Heat Transfer Coefficients Table Chart. Retrieved from https://www.engineersedge.com/heat_transfer/convective_heat_transfer_coefficients__13378.htm

Appendices

Appendix A: Morph Chart

Function	Option 1	Option 2	Option 3	Option 4	Option 5
open/close/access	entire top removes	front panel slides into place	Front panel on hinges	hand holes	Top comes off
					
Lock Shut	pins tapered	latch	snapfit	lock in place	Slide latch
					
Storage	cabinets	drawers			
					
Mobility	wheels	handles			
					
Added height	set on table	stand			
					
Tilt	prop up	rotate on shaft/sphere	prop up mattress holder (lawn chair) https://www.aliexpress.	https://www.youtube.com/watch?v=slUtigh-bLM	https://www.youtube.com/watch?v=6aMWvBw5JPs
					
detach from stand	mobile compartment				
					
water container	combined w/ humidifier				
					
Adjustable Blue Ligh	Up and down	angle			
					
Combinations					
					
Interface					
					

Appendix B: House of Quality

Project:	The Blue Angels														
Date:	January 22, 2020						+								
							+	+							
								+	+						
						-		+	+	+					
			+		+	-		+		+	+				
			Functional Requirements												
		Direction of Improvement	▼	▲	▲	▲	▼	□	□	▲	▲	▼	Customer Competitive Assessment		
Relative Weight	Customer Importance	Customer Requirements	Energy Consumption	Calibration	Strength	Endurance	Weight	Fault Indication	Alarm System	Modular	Intuitive	Maintanence	Our Product	Drager	DRAGER C2000
6%	1	Priority Sensors	●	●				●	●	●	○	○	1	1	1
13%	2	Secondary Sensors	●	●				●	●	●	○	○	1	3	1
6%	1	Plastic Base			●	●	●			○		●	1	1	1
6%	1	Air filter	▽	○			●	○	●	●	▽	●	1	1	1
6%	1	Manual		○				●			●	●	1	1	1
6%	1	Ventilation System	●	○		○	●	○	●	●	○	○	1	1	1
6%	1	Human access				○				○	●		1	1	1
6%	1	Heat System	●	●		●	●	●	●	●	○	○	1	1	1
6%	1	Easy to use						●			●		1		1
13%	2	Backup in case of failure	●				○	●		▽	○	○	1		
13%	2	Easy to carry			●	○	●				○		1		
6%	1	Calibration system	○	▽							▽	●	1	1	1
6%	1	Oxygen system					○				○		1	1	1
13%	2	Inclination			○	○	●			○	●	▽	1	1	1
6%	1	Easy to clean					○			●	●				2
19%	3	Blue light incorporation	●	○						●	●		1	3	3
19%	3	Storage/Support			●	●	○			○	○		1	2	2
13%	2	Transport Support			○		○			●	○		1	3	3
6%	1	Price	●		●	●	○	▽		○	●	●			
		Importance Rating Sum (Importance x Relationship)	418,75	287,5	168,75	187,5	393,75	487,5	337,5	387,5	368,75	356,25			
		Relative Weight	12%	8%	5%	6%	12%	14%	10%	11%	11%	10%			
		Our Product		100%	50 lbs	1 year	50 lbs				100%				
		Technical Competitive Assessment													

Correlations	
Positive	+
Negative	-
No Correlation	

Relationships		Weight
Strong	●	9
Medium	○	3
Weak	▽	1

Direction of Improvement	
Target	□
Minimize	▼
Maximize	▲

Figure 3: House of Quality The customer needs are listed on the left side in descending order of importance. The engineering requirements are listed at the top. The left ranks and compares to already existing products. The Importance ratings are listed at the bottom.

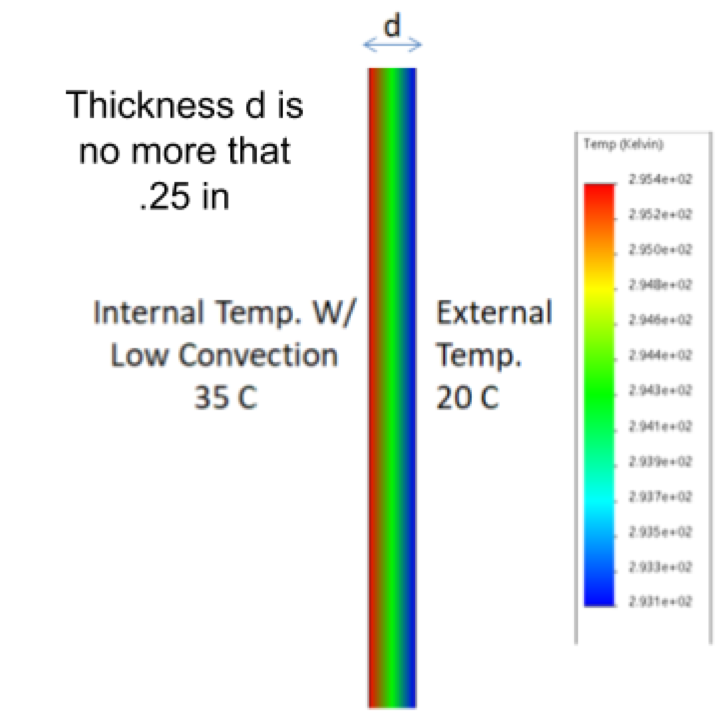
Appendix C: Thermal Analysis

Equations 1-4 are one way to calculate the power. Equations 2,3 and 4 calculate the thermal resistance for a double-pane[11] plexiglass plate, a single-pane plexiglass end plate[12], and the top/bottom single-pane plate[12] respectively. These equations are used in equation 1 to calculate the total heat transfer of the plexiglass hood. The assumption is that $1/4$ inch plexiglass is used for each layer. It also assumes that there are no holes in the system, meaning that the hand doors and grommets used would have to have similar thermal properties to plexiglass, and leave little to no room for air to escape. The results showed 139.73 Watts is dissipated through the Plexiglass.

Because one of the main functions of the incubator is to regulate the infants temperature, it is important to do a thermal analysis of the system and determine what levels of insulation and what amounts of energy are needed. The first thermodynamic evaluations determine an estimated power that the required components need to maintain heat. The goal is to maintain 35°C within the incubator assuming that the minimum external air temp would be 20°C.

The second thermodynamic estimation is evaluated using Solidworks and can be viewed in **Figure 1 of Appendix C**, with the same assumptions that a full model without holes is being used. The heat transfer coefficient inside of the incubator is estimated to be $10\ \frac{W}{m^2K}$, assuming low-speed airflow over the surface of the plexiglass [13], meaning that there is minor forced convection. The external air is assumed to be static, meaning that natural convection would take place. The results show that the heat power dissipated through the plexiglass is approximately 230.93 Watts.

The hand calculated model and the CAD model have two different sets of results because different assumptions are made to best simplify each model. The hand calculations take into account the double-pane, which would be the best-case scenario. Neither take holes or differences in the thickness of plexiglass into account. Thus the final estimated range of required power is 140 Watts to 230 Watts, where 230 would be the worst-case and 140 is an ideal scenario.



Appendix C Figure 1: Heat Dissipation through a single pane of Plexiglass: This figure is a visual of how the heat dissipates through the layer of plexiglass. With the inside of the incubator being on the left side and the outside being on the right side.

$$Q = 2 * \left(\frac{T_{amb1} - T_{amb2}}{R_{tot1}} + \frac{T_{amb1} - T_{amb2}}{R_{tot2}} + \frac{T_{amb1} - T_{amb2}}{R_{tot3}} \right) \quad (1)$$

$$R_{tot1} = \frac{1}{h_1 A_1} + \frac{L}{k_1 A_1} + \frac{L}{k_2 A_1} + \frac{L}{k_1 A_1} + \frac{1}{h_2 A_1} \quad (2)$$

$$R_{tot2} = \frac{1}{h_1 A_2} + \frac{L}{k_1 A_2} + \frac{1}{h_2 A_2} \quad (3)$$

$$R_{tot3} = \frac{1}{h_1 A_3} + \frac{L}{k_1 A_3} + \frac{1}{h_2 A_3} \quad (4)$$

A_1 - Area of double paned plate, meter

A_2 - Area of single paned end plate, meter

A_3 - Area of single paned top and bottom plate, meter

h_1 - Heating transfer coefficient for low speed air flow, $\frac{W}{m^2 K}$

h_2 - Heating transfer coefficient for medium speed air flow, $\frac{W}{m^2 K}$

k_1 - Thermal conductivity of plexiglass, $\frac{W}{m^2 K}$

k_2 - Thermal conductivity of air, $\frac{W}{m^2 K}$

L - thickness of the plexiglass, meter

R_{tot1} - resistance of double paned plate, $\frac{K}{W}$

R_{tot2} - resistance of single paned end plate, $\frac{K}{W}$

R_{tot3} - resistance of single paned top plate and bottom plate, $\frac{K}{W}$

T_{amb1} - temperature of ambient outside air, Celcius

T_{amb2} - temperature of ambient air inside, Celcius