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Design and Analysis of an Efficient Vaccine Cold Chain Box

Shitanshu Devrani* Rahul Kumar* and Sudhanshu Pandey*

Abstract : Human health is one of the most important concerns for the governments around the world. Global organizations such as WHO and PATH have considerable interest in organizing vaccination programs and its cold chain delivery. The problem predominantly persists in Lower-middle income countries (LMICs) like India where due to inadequate infrastructure and lack of Power supply significant losses occur in the cold chain. Significant improvements are required to prevent the loss of costly and precious vaccines during the cold chain. India is notorious for its power shortage problem and resulting power cuts which causes them to lose their potency since they are not within the temperature range of 2-8 ºC. This paper studies the current Vaccine carrier box and cold chain design through the aid of Computer modelling and simulations. Also a novel experimental setup to examine insulation R-value has been devised and studied. Based on this a new design approach is utilized to model a thermoelectric system and early designing is done through the aid of 3-D printing.

Keywords : Vaccine Box, Cold chain, R- value, Heat transfer, thermoelectric system.

1. INTRODUCTION

In the near future, the world population is expected to reach almost 10 billion. This will surely increase the world food and health care demand. A significant percent of food and healthcare medicines like vaccines go to waste due to improper storage and transportation. A primary reason for this is that these products require very specific temperature for storage which is not maintained effectively throughout the cold chain. Focusing on vaccines specifically, there are currently more than 271 vaccines for different diseases and more are on development stage. Each varies in dosage per vial for different manufacturers, hence has a different geometry of vial in which the vaccine is stored and sold in the market. This variation in geometry severely limits the way the vaccine storage space is utilized inside a vaccine carrier box. A typical design as highlighted in this paper, its shortcomings in terms of packing of vaccines tightly enough causes low performance of the vaccine box in terms of storage capacity, storage duration and ergonomics of the system. This is especially true in countries like India where hot climate in the summers can severely decrease the potency of the vaccines.

WHO estimates that reliance on cold chain system increase vaccine cost by 20% in the future and possess significant barrier to patient access in many developing countries. In 2011, UNICEF spent 5 times more on vaccines than it did ten years ago. Thus, a more effective way is required to maintain vaccine viability. Our idea of vaccine trays for storage can be implemented on the current system and also new designs of vaccine boxes can be developed around these trays[1]–[4]. It offers versatility of usage of any pharmaceutical vial and also provides improved mechanical and thermal protection for longer duration.

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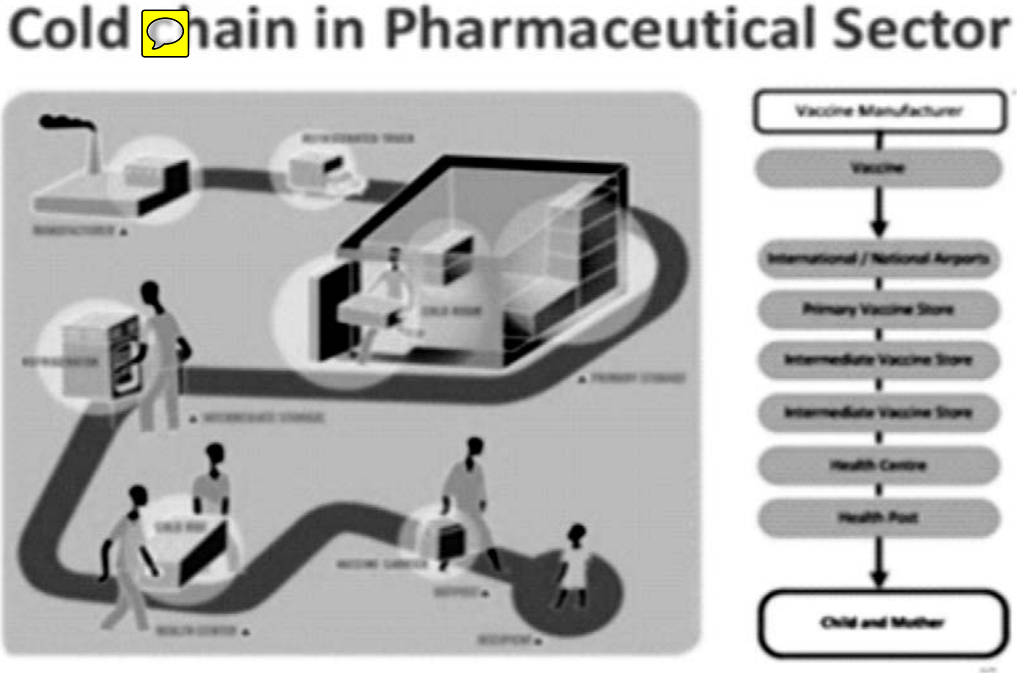


Figure 1: Cold chain applications in pharmaceutical

1.1. Previous Work

Work done by [5], [6]Used an approach to design a box using CAD and FEA analysis backed by Experimental results. They have utilized a simple box design to increase the lifetime capacity of the vaccines. The work has integrated systematic slots around the main vaccine space to store an outer layer of Ice coolant packs and inside a layer of PCM pads available commercially. [7]had an approach especially focusing on the ergonomics of the whole system. They follow an approach with emphasis on Shipping and Transportation of the whole design. They focus on stack ability of sub- parts of the Vaccine case. Some basic limits to the design is its lack of storage capacity for an optimized weight. Other efforts by various innovators have yielded new designs such as the one by Elena Figus wherein the coolant pack integrated with a cotton made hand bag. Although the design conceived is very light and easy to use design but severely lacks in maintaining optimum temperature for longer periods. Also there have been number of efforts to design portable Refrigeration system. [8]–[10]Proposed design include solar power vapor-compression cycles by & vapor absorption cycles by. Besides this [8]explores the proposed solar powered desiccant cooling option. Various strides in portable thermoelectric cooling have been taken as well, work looks into a possible design of specially designed thermoelectric chests but validation and practical optimization in to box featured in the work. Design of solar powered thin film thermoelectric generators have been discussed by[11]stored in remote places and during this period the temperature has to be maintained within certain specified values. Realizing the needs of such requirements, the Department of Science & Technology, New Delhi (Govt. of India. Also various PCM material for cold insulation have been tested throughout literature. Works by have developed robust numerical models which have been experimentally verified.

2. CURRENT DESIGN AND APPLICATIONS

The conventional designs used at SRM hospitals and other government hospitals around are mostly thick insulated bodies with coolant packs inside. The main body is generally a HPDE coated frame around Polyurethane foam (35 to 60 mm thickness). Inside lining can typically consist of Polystyrene coating. The specimen box used for analysis is a 1.6ltr vaccine space capacity box with specifications given in table 1.The company brand is APEX. The coolant packs mostly have a PCM mostly water inside then. The coolant pack is Pre refrigerated or Conditioned. These coolants act as passive cooling components.

Table 1

Specifications of Conventional Vaccine box

Vaccine Storage Capacity	1.6 Liter
Weight Fully loaded	4.5 Kg
Empty Weight	1.99 Kg
External Dimensions	25 x 25 x 30 cm
Internal Dimensions	16.7 x 16.7 x 16.7 cm
Vaccine Storage imensions	9.8 x 9.8 x 9.8 cm
Number of ice packs	4 x 0.4 Liter

This particular box has been designed and analyzed further through experiments.

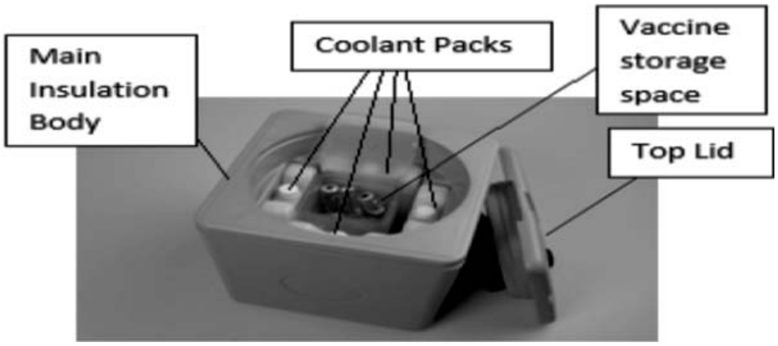


Figure 1: (*a*) Current design of the vaccine box

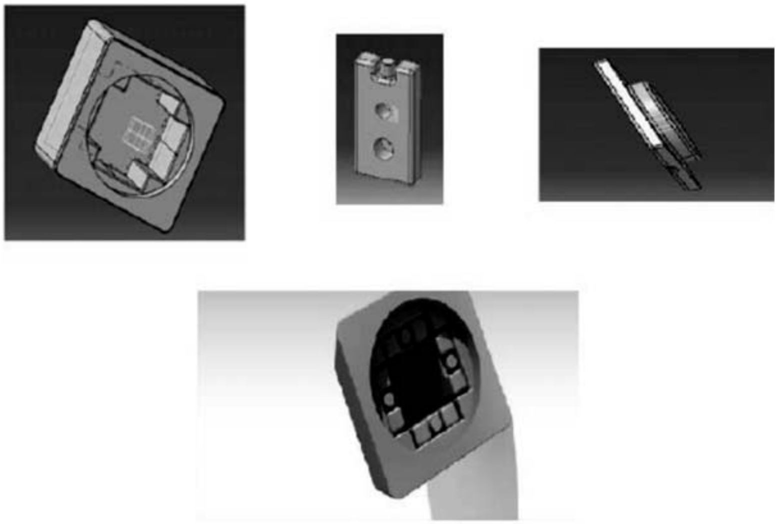


Figure 1: (*b*) Current vaccine box design using Catia V-5

The aim of this exercise was to aid the understanding of the conjugate heat transfer of a vaccine box system[12]–[14], [10]. The system is treated essentially as a passively refrigerated and based on the heat transfer equation appropriate boundary conditions were also applied.

$$\frac{\partial T}{\partial t}+\frac{\upsilon.\nabla T}{\rho C_P} = \frac{k}{\rho C_P}\nabla^2 T+G \qquad (1)$$

$$G = mC_P\Delta T + m\lambda \qquad (2)$$

Where T = Local Temperature,

t = Time,

υ = Air velocity vector,

k, C_p ,ρ = Thermal Conductivity of Polyurethane, Polystyrene, air and HDPE depending on area of application within the system.

G = Passive load of the existing coolants within the system taken as Heat of generation

λ = Latent heat of fusion of the PCM used.

Here the first term is a partial differential of surface Temperature with respect to time. Second term is the convective term. On the right hand side the first term denotes the conductive term followed by a Rate of generation term[10], [15]–[18].

Boundary conditions and settings applied to the solver :

T = 43 °C outside temperature,

T = 6 °C inside vaccine space temperature,

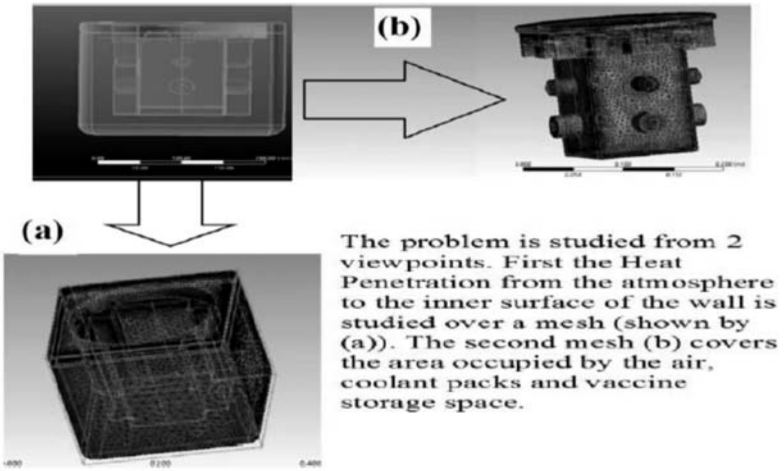
T = 0 °C coolant body temperature,

Convective heat transfer coefficient, $h = 11W/m2K$ at T = 43 °C & $h = 1W/m2K$ at T = 6 °C,

λ = 323 KJ/(kg K) for water

Other important details have been mentioned in appendix

Anysys Workbench Fluent was used to solve the problem. The Finite element model was prepared by using fine hexagonal meshes with minimum nodal size 0f 0.001 m(fig 2). Besides this for the solver used were Energy (1) and Phase change equation (2) were turned on. Also gravity was also turned on. The solution was iterated over 1000 iterations until convergence for steady state model. For unsteady state 100 time steps each of 10 second intervals were chosen and solved.



The problem is studied from 2 viewpoints. First the Heat Penetration from the atmosphere to the inner surface of the wall is studied over a mesh (shown by (a)). The second mesh (b) covers the area occupied by the air, coolant packs and vaccine storage space.

Figure 2: Fine hexagonal mesh of the vaccine box

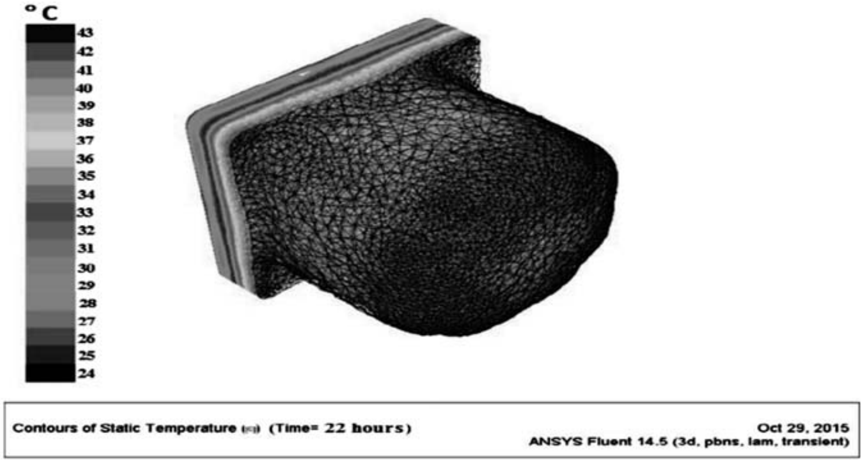


Figure 3: (*a*) Conjugate transient heat transfer analysis of outer casing insulating body for 22 hours

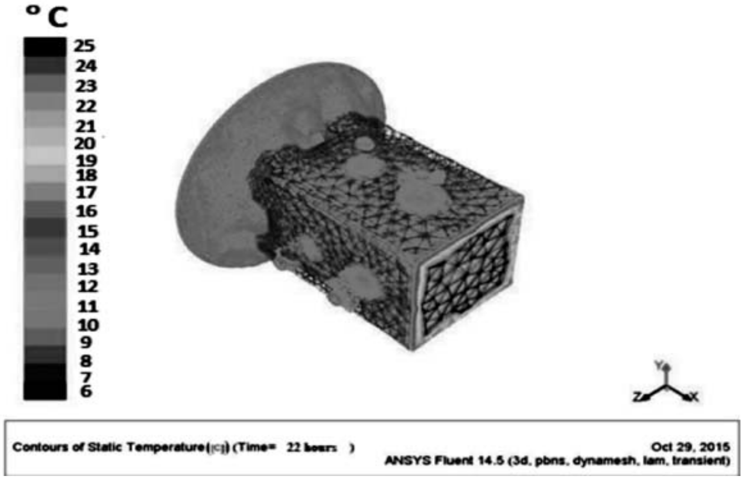


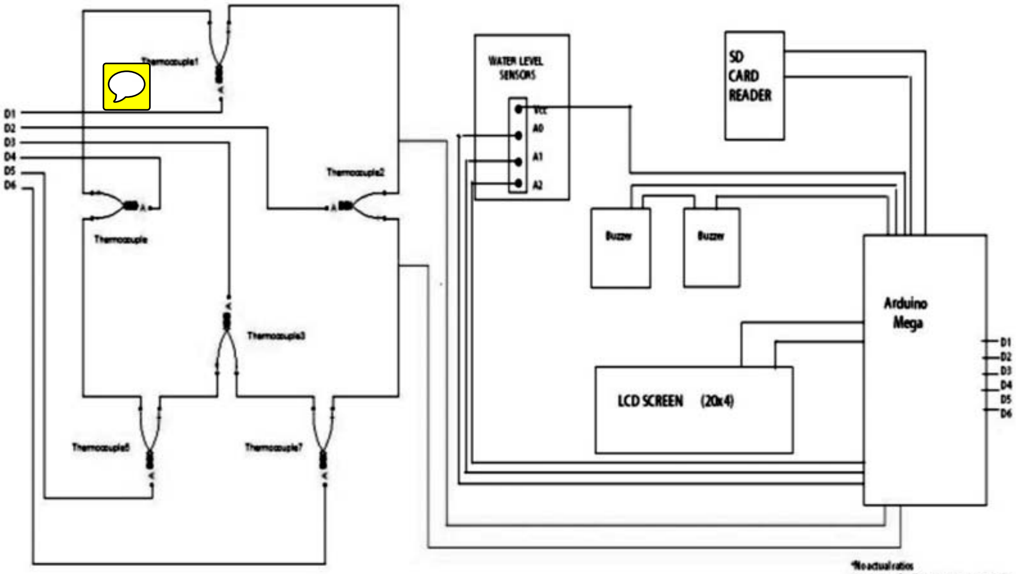
Figure 3: (*b*) Conjugate transient heat transfer analysis of inner casing insulating body for 22 hours

Fig 3*a*, 3*b*. Shows a counter of a 22 hr. transient analysis for the two meshes. Both counters produced here depicts the heat penetration through the base of the box.

3. EXPERIMENTAL WORK

In order to evaluate the Vaccine box performance, we devised a setup to monitor temperatures at various points within the fully closed box .Apart from this, the setup is made to utilize the setup to conduct R- value test. The R-value test is used to find out the resistance value of any packaging or insulation equipment. It is a quantitative measure of the complete resistance to heat flow value for the system in consideration. Principle of the test is that 454 grams (1 lb) of water at 32 must absorb 144 Btu (363 Kcal/151.9 KJ) of heat to melt.[19].

The test setup consist of a regular vaccine box with 6 thermocouple (LM-35) probes inside. Within the vaccine storage space a non-Metallic box with water level sensor probes inserted are placed. Another 7th LM-35 is inserted within this box. All the reading from these 8 sensors are sent to a microprocessor chip. The microprocessor used here is an Arduino Mega 2560 coded to sense the temperature and water level readings with respect to time, Display them on a 16X2 LCD screen and store them on a 16 GB memory stick. The format of storage are simultaneous readings against a time on an Excel spread sheet (ref. fid 4*b*). The code on the Arduino has been given in appendix.



*No actual ratios
*Images are for illustration purposes only.

Figure 4: (*a*) Circuit diagram and schematic representation of the Arduino system

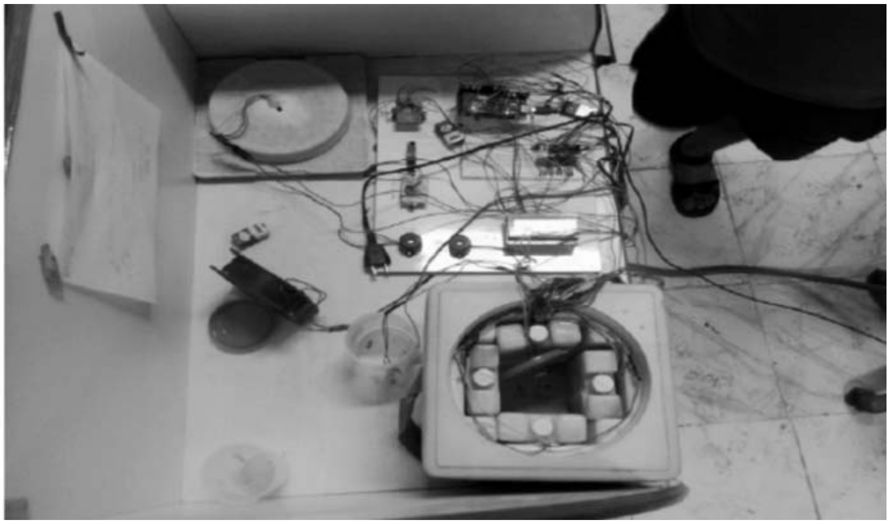


Figure 4: (*b*) Experimental setup to calculate R-value

C. R- value Experimental procedure

A regular quantity of regular ice cubes or crushed stored ice inside a non-metallic bucket which is placed inside the package (Vaccine box in this case). The box is closed and is let to sit at room temperature. The timer in the system takes temperature readings within the box at various points at 30 second intervals. Besides this the water level is continuously monitored inside the non-metallic box through the aid of water level indicators. The amount of ice taken is 100 g, this implies about 150ml of liquid water. Within the geometry of the ice box this amounts to about the maximum water level of 6 cm from the base. Two water levels , one at 3 cm and another at 6 cm are preplaced at the inside lining of the inner wall of the non-metallic container. The water level at 6 cm marks the endpoint of melting.

$$\text{Ice requirement} = \frac{(\text{Box area})\ (\text{Temperature difference})}{(\text{R–value})\ (\text{latent heat})} \tag{3}$$

Where

$$\text{Melt rate} = \frac{\text{Amount of Ice melting}}{\text{Time taken for complete melting}} \tag{4}$$

Box area = inside surface area of package = 1.4 m^2

Temperature difference = outside temperature (room temperature)– inside water temperature (0°C)

Temperature difference = 24 °C – 0°C = 24

Latent heat of H_2O = 323 kJ/(Kg K)

R – Value obtained for different packages is fitted to an empirical formula which takes into account the contribution of conduction, convection and radiation

$$\text{R – value} = 0.27\text{th} + 0.26np + 0.56nf \tag{5}$$

Where

th – Average wall thickness of package

np – Number of plain surfaces

nf – Number of reflecting surfaces

R – value units are $m^2\,°\text{C}/\text{Watt}$.

This helps us analyze the contributions of conduction, convection and radiation into penetration of heat.

$$\text{Ice requirement} = \frac{(\text{Box area})\ (\text{Temperature difference})}{(\text{R–value})\ (\text{latent heat})} \tag{6}$$

Result & Analysis

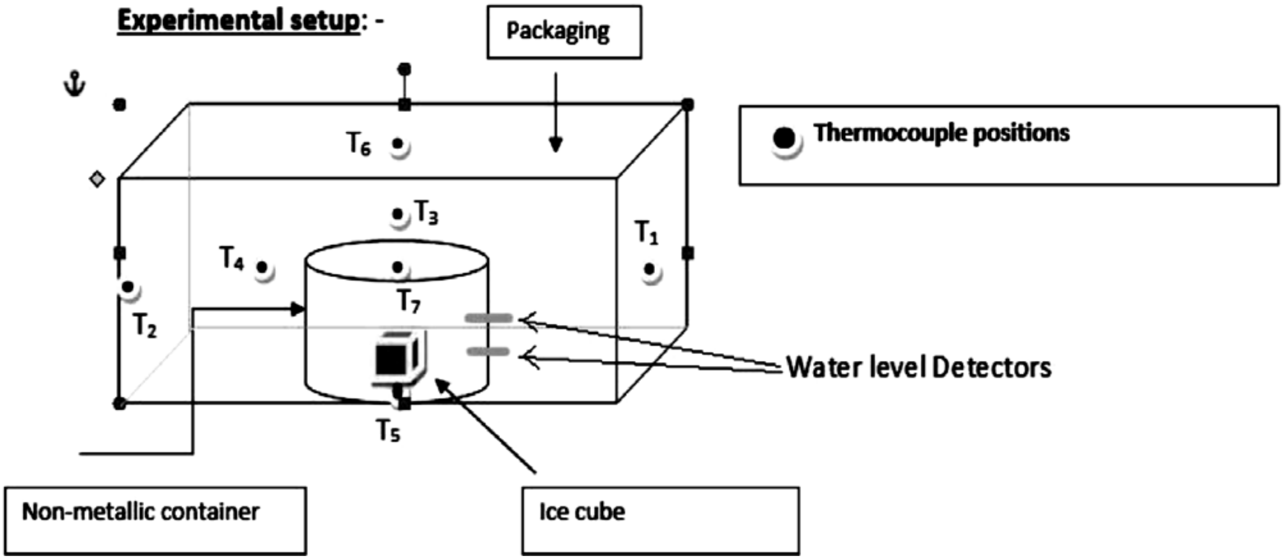


Figure 5: Schematic setup to calculate R-value

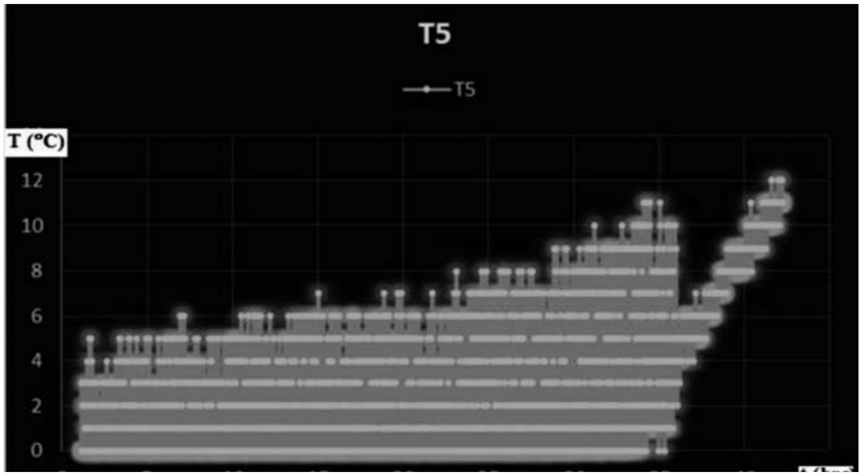


Figure 6: Relation of temperature (T°C) with respect to time(hrs.) inside the vaccine box

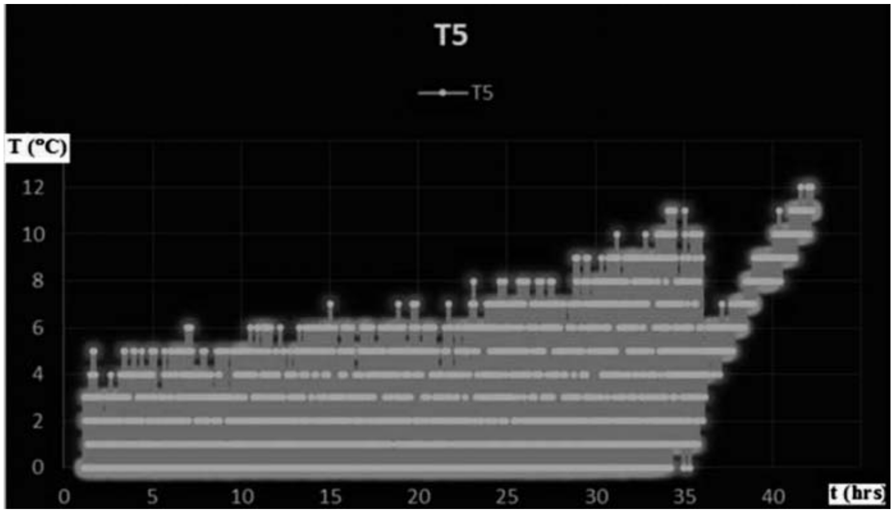


Figure 7: Relation of temperature (T°C) with respect to time (hrs.) at the base of the vaccine box

Temperature (ºC) vs. Time (hr.) plot at various points inside the Box from experiment shown in Fig.6. at ambient temperature of 26ºC. Each thermocouple attached has been named accordingly in the schematic diagram (fig. 5)of the setup and the graph involved. The essential conclusion we draw from this is that within a period of 35 hours the temperatures for all the sensors surpasses the vaccine safe keeping temperature (2-8 ºC). Figure 7 depicts the Temperature over time reading for T5 sensor located at the inside lining of the Base of the box. It is explicitly plotted because among all the sensors placed at various places within the box, it is this base sensor reading where large temperature fluctuations over time are consistently observed. This fluctuation points towards temperature gradients developed within the box leading to thermal shocks which limits the duration of vaccine safekeeping time (35 hr. for 24ºC). Duration goes significantly down for higher temperatures as confirmed by local doctors at the Community Medicine Department at SRM medical Hospital. This significant and rapid heat transfer from the base has also been confirmed by simulation developed in the previous sections. The reason for this is fairly intuitional as the base is the continuous source of conduction where in the inside lining does not contain an Ice coolant. This results in convective air currents within the box leading to thermal gradients generated within the system.

Based on the results obtained from the experiments

The water level reaches the 6 cm water level sensor at 46889th second. This amounts to about 13.02 hr.

Using (4), $$\text{Melt rate} = \frac{0.1\text{Kg}}{13\text{hr}} = 0.00768\,{}^{\text{kg}}\!/_{\text{hr}}$$

Using (3), $$\text{Systeme R} - \text{Value} = \frac{0.1\ \text{Kg}}{13\ \text{hr}} = 0.00768\,{}^{kg}\!/_{hr}$$

Using (5), $$4.724 = 0.27(9) + 0.26(5) + 0.56(2)$$

$$4.724 \approx \underbrace{2.43}_{\text{Conduction}} + \underbrace{1.\ 3}_{\text{Deviation}} + \underbrace{1.12}_{\text{Radiation}}$$

From the result obtained, the individual contribution to heat transfer is 51.43% conduction, 27.51% Convection and 23.7 % radiation. These numbers suggest the contribution of each mode of heat transfer within the time frame of cold insulation of the box for vaccine storage.

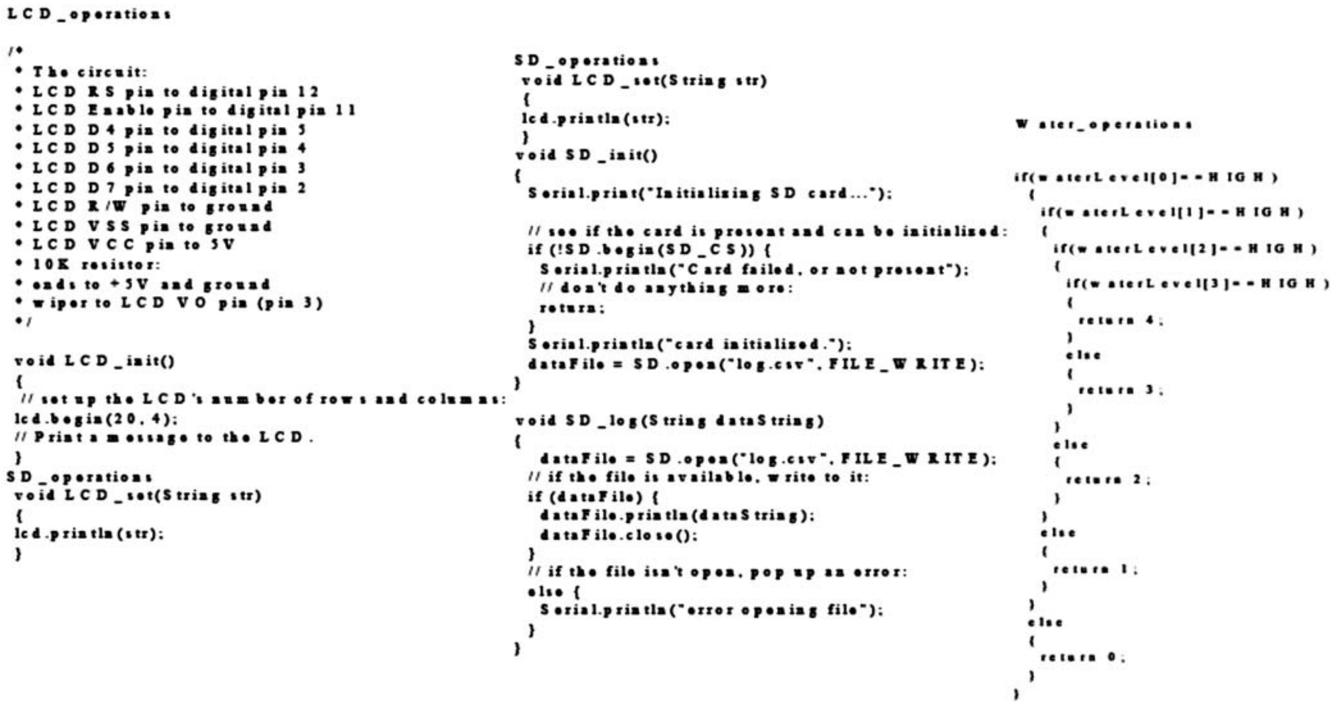
The minimum ice requirement of a system operating at 43 ℃ outside temperature can be calculated by using (6),

$$\text{Ice requirement} = \frac{(1.4\ \text{X}\ 6)(43)}{(4.724)(323)} = 0.236\text{kg} \approx 250\text{g}$$

Program code

```
Vaccine_storage_space

#define lcdRS 22
#define lcdRW 24
#define lcdE 26
#define lcdD0 28
#define lcdD1 30
#define lcdD2 32
#define lcdD3 34
#define lcdD4 36
#define lcdD5 38
#define lcdD6 40
#define lcdD7 42
#define lcdBP 44
#define lcdBM 46

#define SD_CS 48
#define SD_MOSI 50
#define SD_SCK 52
#define SD_MISO 51

int tempPin[7] = {A0.A1.A2.A3.A4.A5.A6}:
int waterPin[4]= {A9.A10.A11.A12}:
//--------------------------Pin Declaration Ends----------------//

#include<LiquidCrystal.h>
#include <SPI.h>
#include <SD.h>
```

```
LiquidCrystal lcd(lcdRS.lcdE . lcdD4. lcdD5. lcdD6. lcdD7);
File dataFile;

int tempData[7]={0.0.0.0.0.0.0}:
int waterLevel[4]={0.0.0.0}:
void setup() {
Serial.begin(115200);
LCD_init():
SD_init():
}
//time.temp0-temp7.water4;
void loop() {
 String dataLog=String(millis()/1000);
 read_temp():
 for(int i=0;i<7;i++)
 {
  if(i<7)
  dataLog+=".":
  dataLog+=String(tempData[i]);
 }
 dataLog+=".";
 dataLog+=String(readWaterLevel()):
 SD_log(dataLog):
 Serial.println(dataLog):
 LCD_set(dataLog):
 delay(2000):
}
```



```
LCD_operations

/*
 * The circuit:
 * LCD RS pin to digital pin 12
 * LCD Enable pin to digital pin 11
 * LCD D4 pin to digital pin 5
 * LCD D5 pin to digital pin 4
 * LCD D6 pin to digital pin 3
 * LCD D7 pin to digital pin 2
 * LCD R/W pin to ground
 * LCD VSS pin to ground
 * LCD VCC pin to 5V
 * 10K resistor:
 * ends to +5V and ground
 * wiper to LCD VO pin (pin 3)
 */

 void LCD_init()
 {
  // set up the LCD's number of rows and columns:
 lcd.begin(20, 4);
 // Print a message to the LCD.
 }
SD_operations
 void LCD_set(String str)
 {
 lcd.println(str);
 }
```

```
SD_operations
 void LCD_set(String str)
 {
 lcd.println(str);
 }
void SD_init()
{
  Serial.print("Initializing SD card...");

  // see if the card is present and can be initialized:
  if (!SD.begin(SD_CS)) {
    Serial.println("Card failed, or not present");
    // don't do anything more:
    return;
  }
  Serial.println("card initialized.");
  dataFile = SD.open("log.csv", FILE_WRITE);
}

void SD_log(String dataString)
{
    dataFile = SD.open("log.csv", FILE_WRITE);
  // if the file is available, write to it:
  if (dataFile) {
    dataFile.println(dataString);
    dataFile.close();
  }
  // if the file isn't open, pop up an error:
  else {
    Serial.println("error opening file");
  }
}
```

```
Water_operations

if(waterLevel[0]==HIGH)
 {
   if(waterLevel[1]==HIGH)
   {
    if(waterLevel[2]==HIGH)
    {
     if(waterLevel[3]==HIGH)
     {
      return 4;
     }
     else
     {
      return 3;
     }
    }
    else
    {
     return 2;
    }
   }
   else
   {
    return 1;
   }
 }
 else
 {
  return 0;
 }
}
```

4. RESULTS AND DISCUSSIONS

In the previous sections, it has been highlighted that the current box has certain shortcomings. Some of these are Constant thermal exposure of entire batch of vaccine every time the lid is opened to take out a vaccine. This causes frequent thermal shock to all the vaccines inside. No defined usage of actual storage space leads to relatively low number of vaccine storage typically 5-10 vials for 1.6 litre storage space capacity box. Experiments (fig.2 & 4) and literature survey show that there is development of temperature gradient within the box (especially at the base). This is particularly evident in the base of the box where continuous fluctuations in temperatures are followed by a sharp rise. This implies significant heat transfer from the bottom.

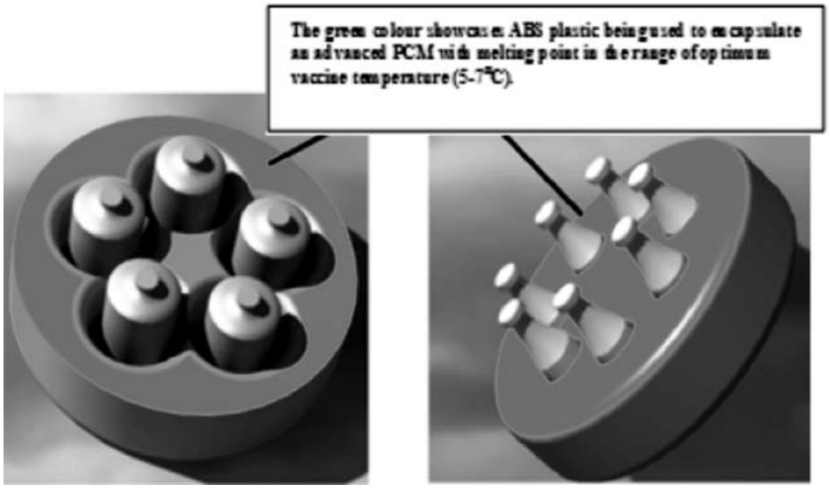
Also Coolant packs are not held in their position and while carriage in difficult terrain undergoes frequent collision with the carrier walls, vaccine vials. This causes damage to vials, coolant body leading to leakage. Also this kind of contact can cause freezing of vials below the required temperature leading to them loosing potency. One of the main problem is Inadequate vaccine safe keeping time for long immunization programs (1 -1.5 days for ambient temperature 23-30 °C ad <1 day for summer temperatures ≥ 40 °C). Separate thermal conditioning of the vaccine and coolant packs is needed before an immunization program. Barring all these limitations of the current design, we propose a new design.

Such a system should not only keep the potency of vaccines for longer durations but should also be more ergonomic to the cold chain.

Following are the novel features of such a design.

TRAY DESIGN

According to our literature survey and studying of various designs there seems to be lack of a system for efficiently utilizing the storage space at the centre of the box. This is critical since utilizing this space will not only ensure systematic and safe storage of vaccines but also improve the accountability for maintaining an inventory for keeping track of vaccines stored per carrier box. A tray stacking system such as the one depicted one is at the core of our design. Such a tray made up of a suitable plastic with moderate thermal conductivity (0.5-1 W/mk) and structural load capacity can potentially transform the system. A special PCM is encapsulated within these trays. An early design of such a tray has been 3-d printed.



The green colour showcases ABS plastic being used to encapsulate an advanced PCM with melting point in the range of optimum vaccine temperature (5-7°C).

Figure 8: Novel tray design at the core of the system

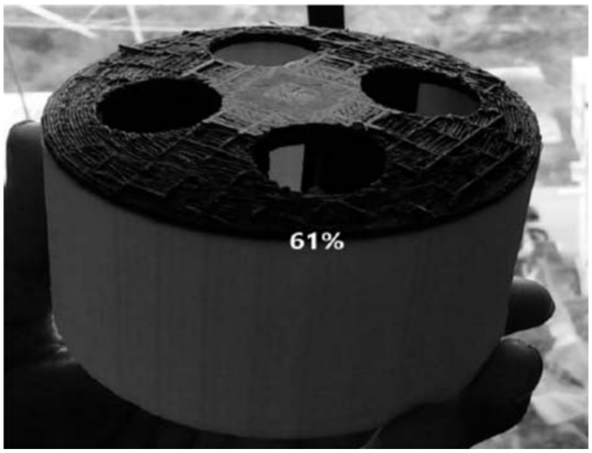


Figure 9: Early design of the 3D printed tray

B. PCM Integration

Thermal energy storage (TES) is a technology with a high potential for different thermal applications. It is well known that TES could be the most appropriate way and method to correct the gap between the demand and supply of energy and therefore it has become a very attractive technology. The energy storage density could be increased using PCM, having a phase change (latent heat) within the temperature range of the storage. Considering the temperature interval $\Delta T = T_1 - T_2$ the stored heat in a PCM can be calculated as follows:

$$Q_{latent} = \int_{T_1}^{T_{PC}} C_S . dT + \Delta H_{1S} + \int_{T_{PC}}^{T_2} C_1 . dT \tag{7}$$

Where Q latent is the sensible and latent heat stored and ΔH ls the heat of fusion at the phase change temperature TPC. Latent heat TES is particularly attractive due to its ability to provide

High-energy storage density per unit mass. This means that in a specific application where the temperature range is important, for instance in transport of sensitive temperature products, the use of PCM becomes very useful since it can store material at constant temperature corresponding to the phase-transition temperature of the PCM. In this paper we use PCM as thermal energy storage material so that it can prevent super cooling of the vaccine.

PCM of choice in this case is 1-Decanol as Hawes et al. studied the thermal performance of PCMs (Decanol, Paraffin, and Tetradecanol) and reported good results. More so such results are very desirable to our needs. Using a similar approach for modelling used earlier section and equations (1) & (2), we run another steady state analysis for such a tray system. Results show that such a system has the ability to minimize temperature gradients developed through convection of air within the storage space. Such tray have PCMs with melting point within the range of 4-6°C. Trays with PCM melting inside simultaneously can reduced the differential temperatures by creating subsystem within them(fig. 10). Besides this, the thermal exposure when the lid is opened is limited to the tray in use. This protects the trays kept underneath. Also sufficient protection is attained by such a system, this is critical since our results on the current design show that maximum heat transfer for a fully closed box is from the base.

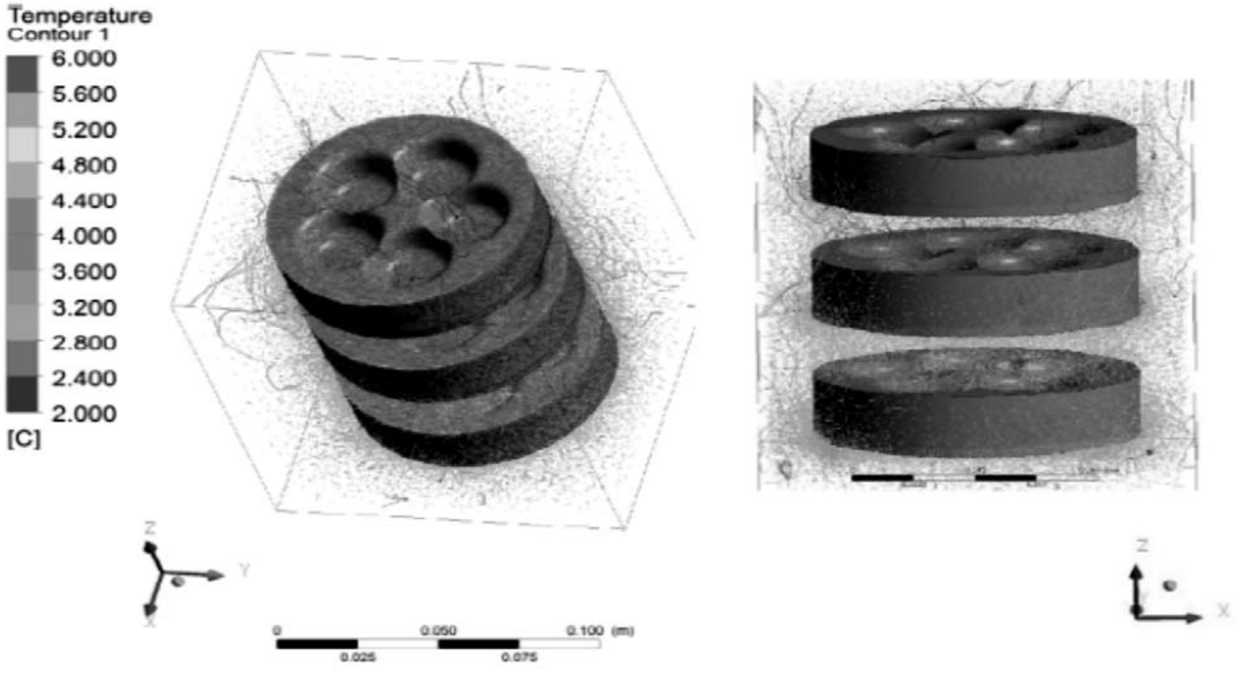


Figure 10: Conjugate heat transfer analysis of the tray system

Thermoelectric cooling

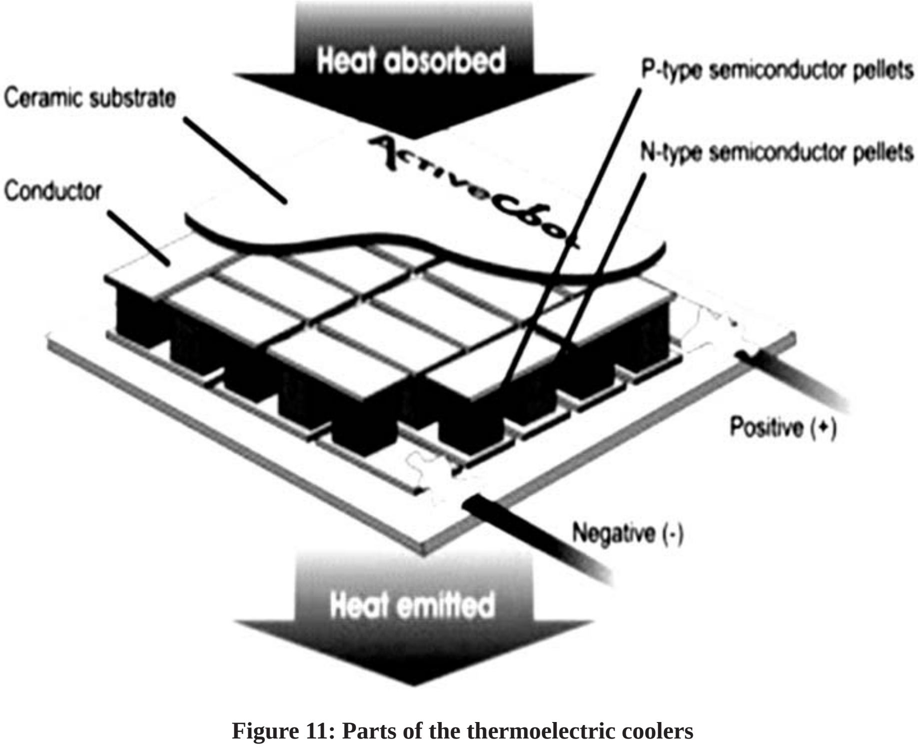


Figure 11: Parts of the thermoelectric coolers

Thermoelectric coolers (TECs), also known as Peltier coolers, are solid-state heat pumps that utilize the Peltier effect to move heat. Passing a current though a TEC transfers heat from one side to the other, typically producing a heat differential of around 40°C or as much as 70°C in high-end devices that can be used to transfer heat from one place to another.

D. The Complete Design

The complete design incorporates PCM encapsulated tray design assisted by thermoelectric plates. In the conventional design 1.6 kg of water is utilized for cooling within the coolant packs. The tray designed are meant to hold about 250 g of PCM within. Three trays such as this cumulatively take about 800 g of the net weight. This helps us to reduce the mass of water within the coolant packs as now we hold about 125 g of water per coolant pack. Cumulatively this would amount to about 500 g of water. Thus the TES mass employed is about 1.3 Kg. On the other sides of the coolant packs 4 Peltier plates are employed, 3 in the sides and 1 at the bottom. These plates are run by a 60 W solar chargeable battery system. This is thoroughly calculated after analysing and quantifying the thermal load involved in this cooling space. The cooling load calculated is 18 W. The system is optimized by the help of a power distributer attached to the battery, the distribution of power is controlled by a microprocessor which gets temperature and humidity readings reported by the probe within the box. The ice coolants and PCM are assisted by the Peltier plate. The outside insulation is cylindrical in shape since after a sphere, cylinder is the shape with lowest surface area to volume(S/V) ratio. The lower the S/V ratio, the lower will be the rate of heat transfer to the surrounding.

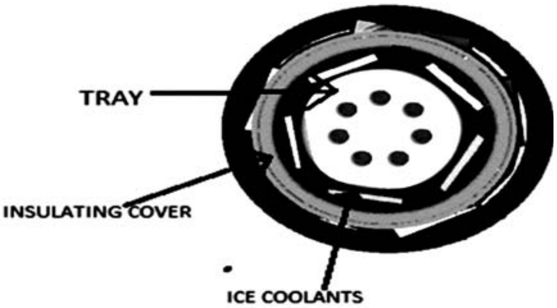


Figure 12: (*a*) Top view of the proposed vaccine box

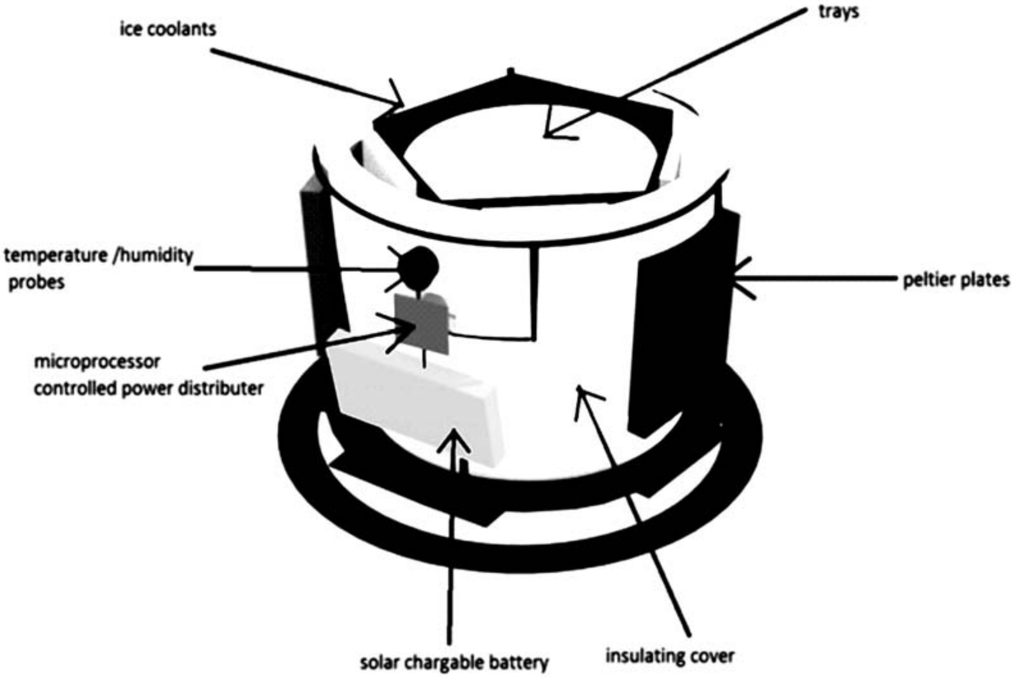


Figure 12: (*b*) Side view of the proposed vaccine box

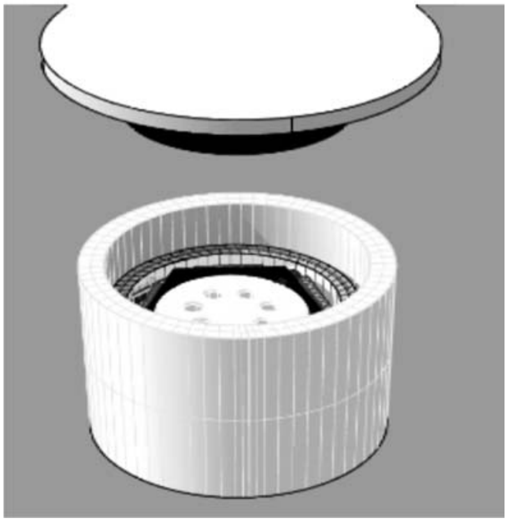


Figure 13: Fully insulated vaccine box

6. CONCLUSIONS

The study here access the performance of the current cold chain box used for immunization programmes. Findings point towards a need for an improved and optimized design which not only keeps the potency of vaccines for longer durations but also makes the cold chain more ergonomic. The design proposed here utilizes advanced PCMs as thermal energy storage systems to eliminate the limitations of the current design.

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