Vacuum insulation panel (VIP) integrated vaccine storage device

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Brief Layout

- Brunel University London
- Introduction to the problem
- Modelling procedure adopted
- Results & final design
- Conclusion and ongoing work

Brunel
UNIVERSITY
LONDON

Key Facts :

- **T.H.E. survey of new Universities established in last 50 years recently ranked Brunel 3rd in the UK and 25th world-wide**

- Recruit students from over 100 countries

Engineering and Design

Formed in 2004 - One of the Largest Engineering and Design Schools in the UK

- 1700 Undergraduate students
- 1000 taught Postgraduate students
- 370 research students and research fellows
- **110 Academic Staff**
- 35 Administrative Staff
- 40 Technical Staff

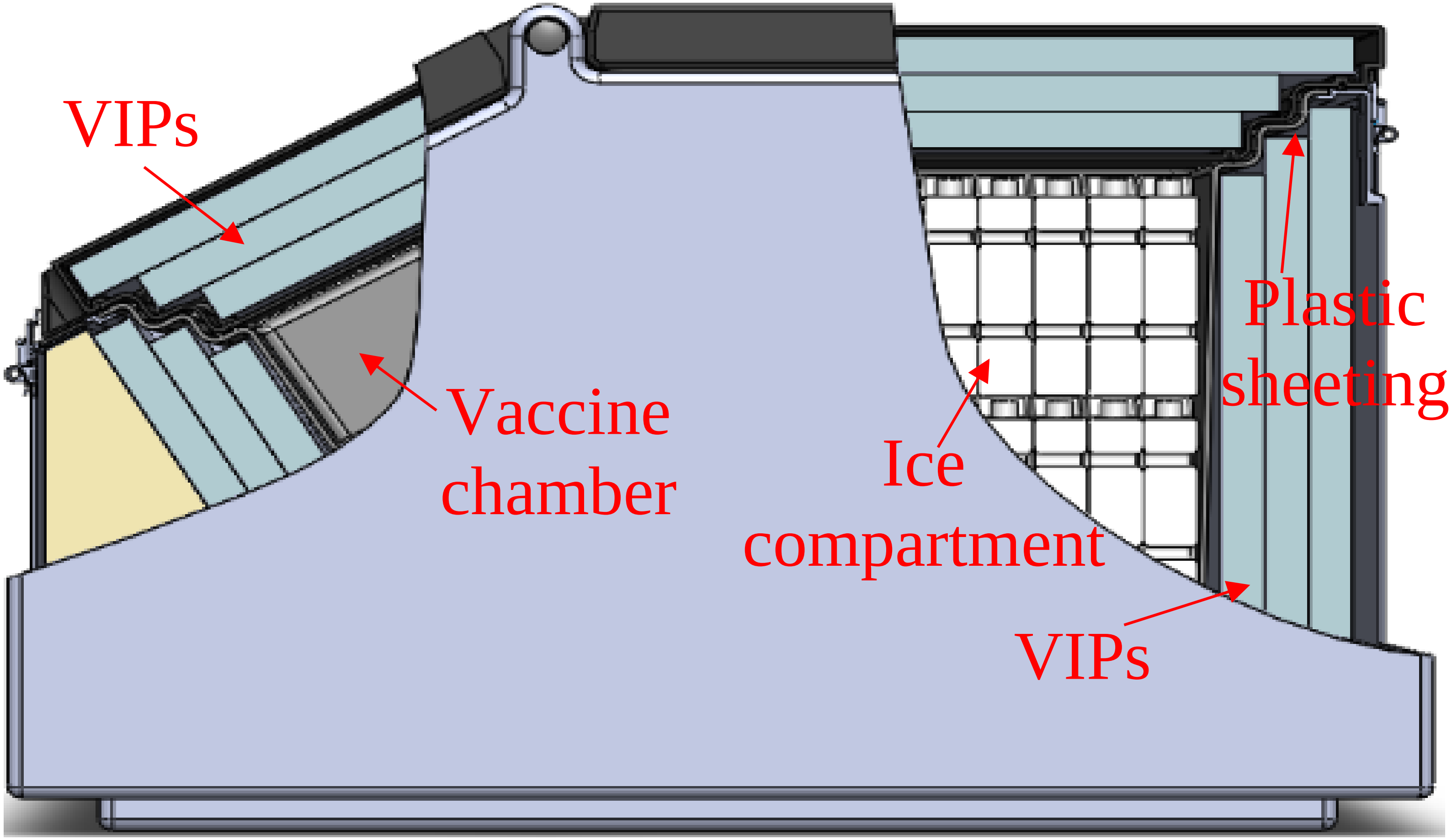
Background

- Vaccines for the prevention of many life-threatening childhood diseases must be stored at a temperature of 2-8 °C to avoid any degradation.
- This is a steep challenge
- Worldwide 1.3 billion people, 18% of the global population, have no access to electricity
- Development of a vaccine storage device (VSD) intended for storing vaccines at 4 ˚C to 8 ˚C for up to 35 days without any active means of cooling
- Freezing will irreparably damage many vaccines

Main Components of the VSD

- The VSD comprises an innovative arrangement of VIPs
- Ice compartment
- Vaccine compartment
- Sure Chill element
- The Sure Chill element transfers heat from the vaccine compartment to a store of ice packs, using the anomalous expansion behaviour of water to maintain a temperature of 2-8 °C. The element works on the principle that water is most dense at 4 °C, thus creating convection currents throughout the Sure Chill element to self – regulate the temperature of the vaccine compartment.

Construction Details of the VSD



Construction Details of the VSD

Methodology Adopted to Design & Develop the VSD

- Computer modelling using COMSOL-Multiphysics to predict the geometric and physical specifications of components to achieve a ‘cold holdover’ life of the device (time taken for the temperature of the vaccine compartment to rise to 10°C)
- Physical construction & Lab testing under WHO prescribed day-night temperature cycle of 43 °C and 25 °C with a ramp of three hours on either side
- A range of VIP types & sizes and different materials for VSD parts; The ice was loaded at an initial temperature of -25 °C
- Improvements in design
- Final prototypes developed and deployed in field for testing under real life ambient conditions

Heat Transfer Phenomena in the VSD

- Complex, multi-mode, transient and simultaneously occurring heat exchanges
- Convective heat transfer between the room air and the outer surfaces of the VSD
- Radiative heat transfer between the room and the vertical walls and the top of the VSD
- Conductive and radiative heat transfer between the VSD and room floor
- Heat exchanged with the room air infiltrating into the VSD
- Heat exchange with room air due to the VSD door opening to remove vaccine vials
- Convective heat transfer as the infiltrating air circulates in gaps between adjacent VIPs and the VSD surfaces (VIP envelopes are folded on the edges which leave unwanted gaps between them and neighbouring surfaces)
- Conductive heat transfer through the VIPs
- Radiative exchange among components of the VSD such as VIPs and ice compartment
- Conductive heat transfer through the solid surfaces such as PU foam insulation and the plastic casing
- Sensible and latent heat transfer phenomena in the ice
- Convective heat transfer phenomena taking place inside the Sure Chill element driven by the anomalous expansion of water

Effect of geometry, Manufacturing Tolerances and Opening of the VSD

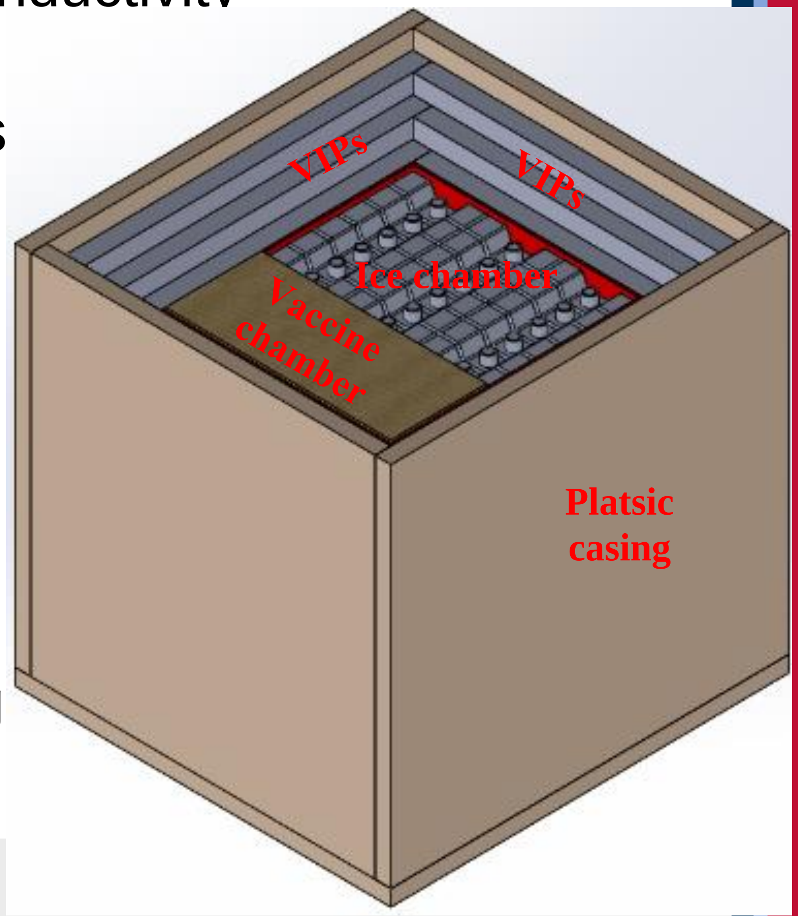
- Complexity is added by the geometry (shape and size) of the vaccine storage device,
- The VSD is expected to be opened several times a day for removal and replacement of vaccine vials.
- The opening of the lid was assumed to completely replace the inside air with the room air at 43 °C. In reality, the opening of the lid will additionally result in convective loss as the room air will rush into and out of the vaccine chamber when the lid is open. This will create a significant heat gain to the device.

COMSOL-Multiphysics Computer Model

- Temperatures of the various components of the VSD are unknown
- Predicting these temperatures to analyse the device performance involves solving complex and coupled heat & fluid flow equations for each component
- COMSOL Multiphysics software was adopted to predict the time dependent temperature of various components over the full duration of the storage
- Ice temperature adopted as an indicator of device ‘state of charge’ (remaining cold life)
- A series of CAD models of the VSD were used to simulate the performance under a range of insulation level, geometric and shape features
- An iterative procedure was employed to avoid the problems associated with Boolean geometry operation due to overlapping features, intersecting features and tiny gaps within the model that caused meshing problems for COMSOL multi-physics analysis

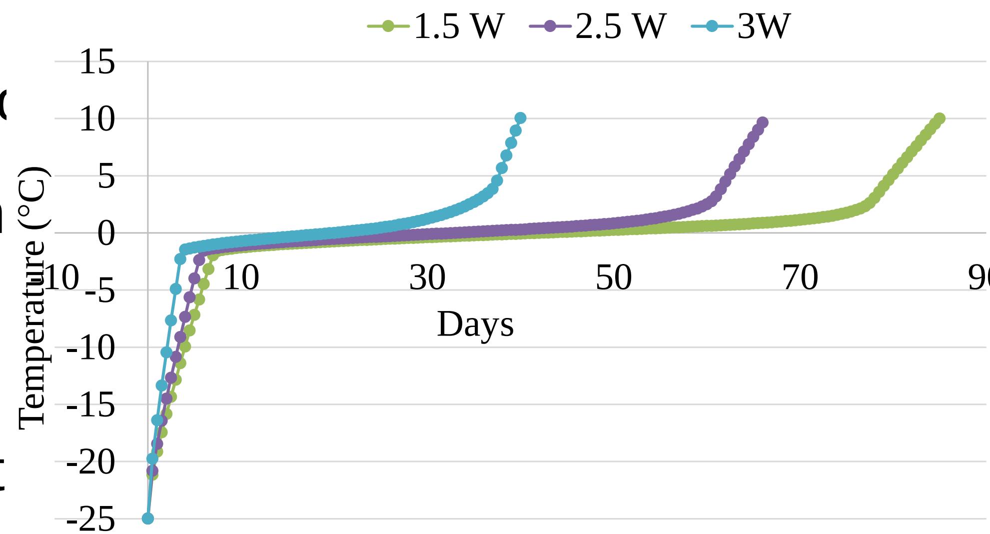
COMSOL-Multiphysics Computer Model

- Started with simulating a simpler cuboid VSD with all sides insulated with square cross section VIPs with an outer plastic shell and an inner ice block core. The VIPs were assumed as one VIP panel of equivalent thickness
- The plastic casing was identified as a major source of heat gain due to its significantly higher thermal conductivitv
- The results of the COMSOL model were validated with experimental results
- The model was then extended to add extra geometrical features, such as outer shell, separate VIP panels, merged shell, shell extension to outer surface, vaccine chamber and the Sure Chill element
- The operational features such as the day-night cyclic temperature variation, heat flux due to opening and the closing vaccine chamber lid were added



Model Stability & Heat Flux Input Factor

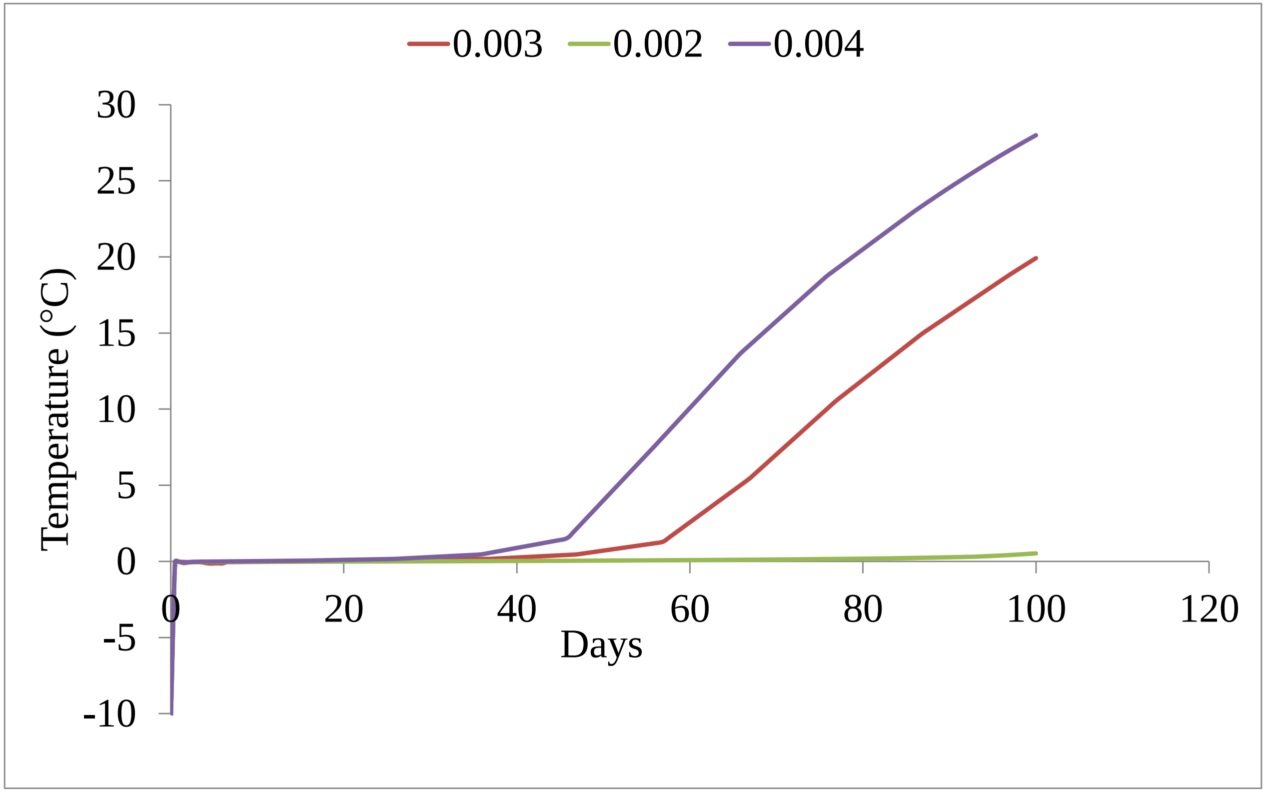
- The initial conditions: ice block -25 °C and VIP surfaces 43 °C
- The problem was posed by the hugely different temperatures on the nodes which were at the interface of the ice block and VIP/ambient. This issue was resolved using a thin layer feature to gradually 'turn on' the surface conductivity
- The phase change of ice (to liquid water) was simulated using stepped specific heat function of 1.6 x 10^5 J/kg to allow melting over 2°C (-1°C to 1°C)
- A constant heat flux input fact was adopted to account for heat gain due to opening of th VSD and manufacturing tolerances
- A heat flux input factor of 3 W was adopted based on validat against the experimental data.
- This factor will change as the design features of the VSD change



Boundary Conditions Adopted

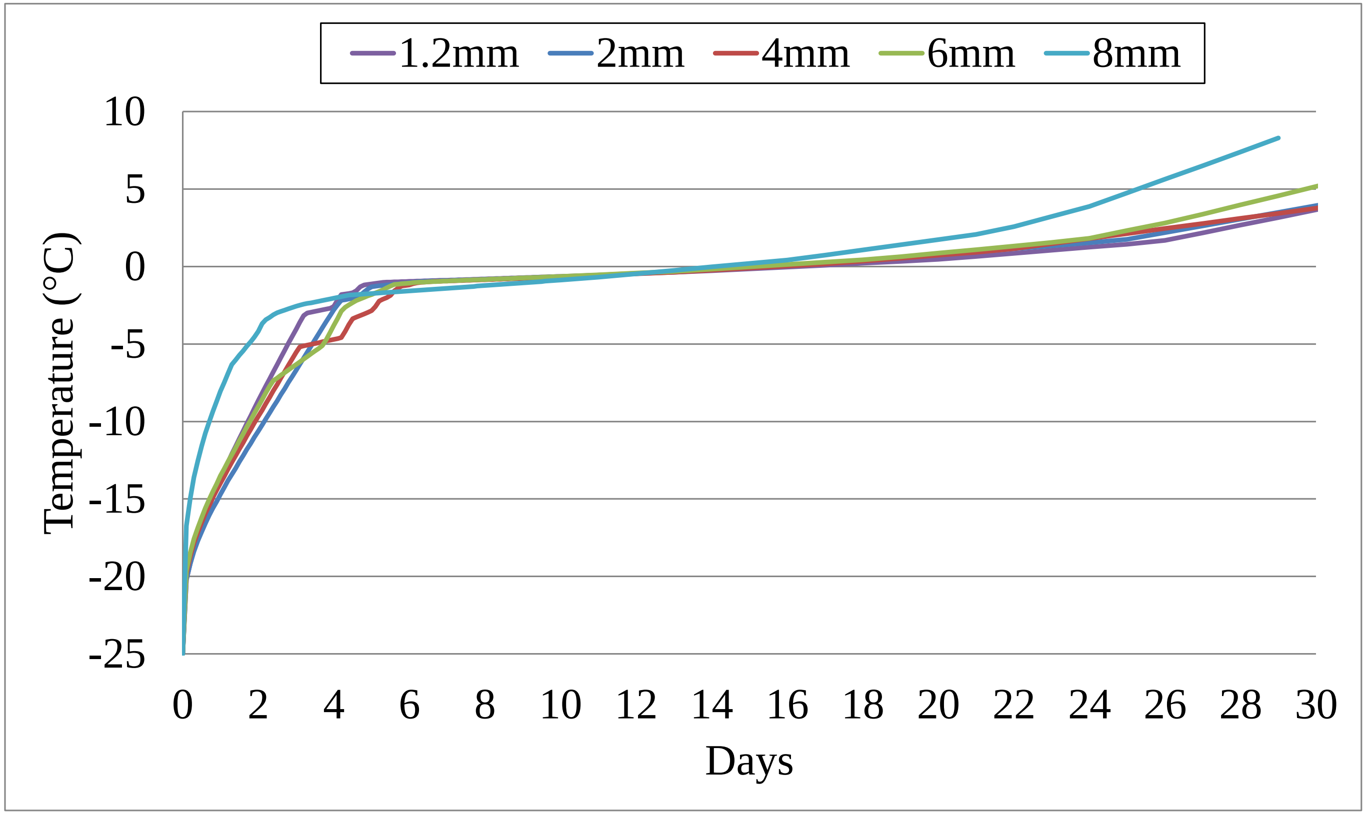
- Room conditions were simulated assuming either a fixed temperature of day (43 °C) and night (25 °C) or by assuming a ramp of three hours in the morning and evening (WHO)
- Day and night each was assumed to be 9 hrs long
- The ice load comprising 54, 0.6 litre ice packs was simplified for the model to a single block of ice of volume 32.8 litres
- Heat was allowed to be exchanged between room environment and the VSD by conduction, convection and radiation
- The thermal conductivity of the VIP from 3-6 mW/m.K.
- Different thicknesses of plastic casing (1.2 mm- 8mm)
- The challenge here is to identify and evaluate the relative (and absolute) effects of simultaneously occurring factors such as thermal bridging due to plastic sheeting (casing), air infiltration and door opening on ice temperature.

Effect of VIP Thermal Conductivity



Effect of Plastic Shell Thickness

- A thinner plastic casing would yield a longer holdover period



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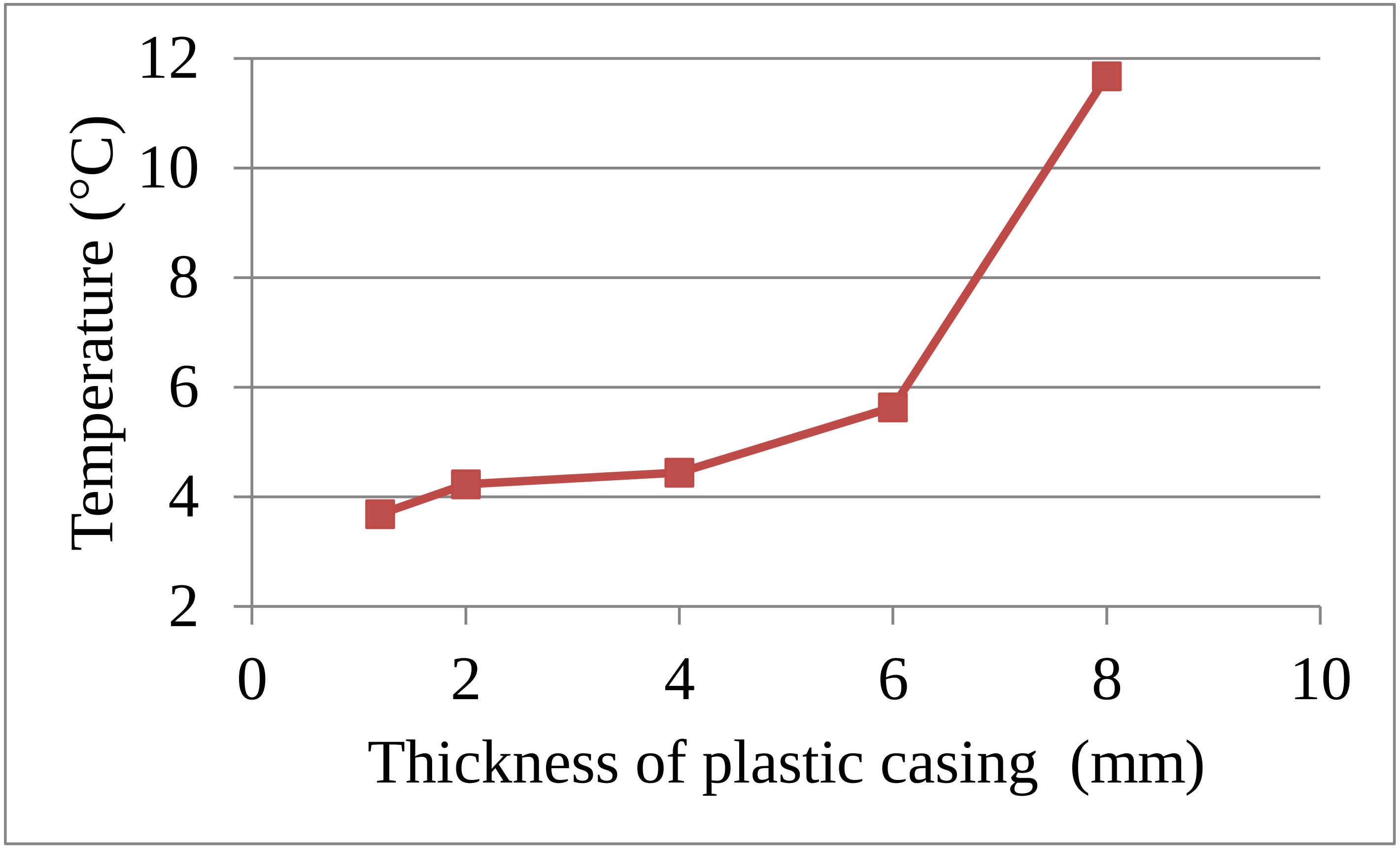

Conclusions

- A comprehensive computer model developed
- Validated against the simultaneously run experimental programme
- To extend the cold holdover life, it is strongly felt that the plastic casing will require reducing in thickness to minimise heat flux from the surroundings
- Heat flux is presumed to occur along the VIP edges where spare envelope material is folded preventing full surface to surface contact between adjacent VIPs.
- The gap between any two adjacent VIPs has been found to be a path for circulation of air inside the vaccine storage device
- It has been found that with the proposed VIP and geometric configuration the vaccine can be stored in the chamber for up to 30 days without causing any degradation
- Prototypes are under test to demonstrate practical ways of achieving this.

Acknowledgement

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Thank you for your attention!