School of Engineering

VaxVac: Keeping Vaccines Safe, Anywhere

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April 1st, 2025

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Assignment 3 5B3 Advanced Thermal Fluids Design

Executive Summary

The VaxVac project addresses the critical challenge of vaccine wastage in high-temperature environments by proposing an innovative portable pressurized refrigeration system designed to maintain vaccine efficacy. With global vaccine wastage rates exceeding 50%, largely due to ineffective temperature control and logistical issues, VaxVac aims to provide a reliable solution for philanthropic organizations operating in remote or resource-constrained regions.

The design leverages vacuum storage technology to minimize heat transfer while maintaining vaccines within the optimal temperature range of 2°C to 8°C for up to 10 hours. Featuring an aluminium shell, UF foam insulation, and a hand-pump-operated vacuum system, VaxVac is robust, lightweight, and easy to maintain, making it ideal for field use. Analytical and computational fluid dynamics (CFD) simulations validate its thermal performance, ensuring uniform temperature distribution and compliance with vaccine storage requirements.

Proposed Technical Approach

Problem Statement and Target Market

Philanthropic organisations working in high-temperature environments are seeking proposals for an affordable, portable refrigeration system to ensure the viability of vaccines in these extreme conditions. Such programs will always have some form of vaccine wastage, with the World Health Organisation (WHO) estimating a wastage percentage of over 50% globally. This is often due to issues with logistics and effective temperature control. For example, traditional solutions such as iceboxes often have problems with vaccine freezing if they are not properly handled or if icepacks are not adequately conditioned.

The challenge is to develop a vaccine carrier that is capable of both keeping the vaccines at the required temperatures and being robust against damage while being portable enough for the average volunteer to carry. The vials have a nominal operating temperature of 4°C and an overall range of 2°C to 8°C. These temperatures must be maintained over a minimum of 10 hours, and additionally, the temperature of the vials should remain uniform. The design should not rely heavily on electricity, if at all, and be easy to maintain and repair with minimal training.

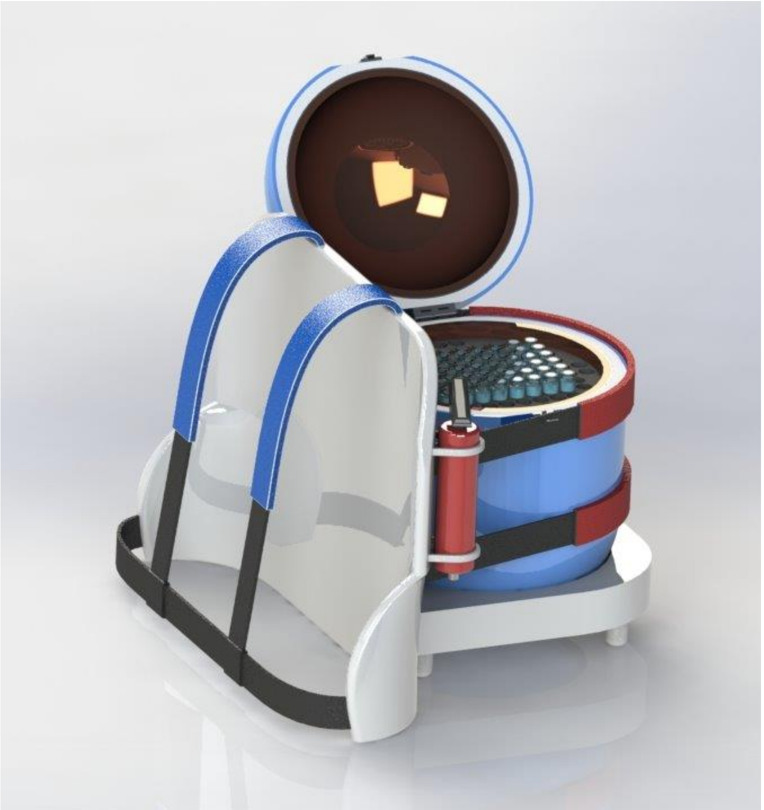

Figure 1: VaxVac

Technology/Design Overview

Ensuring vaccines are kept between 2 °C - 8°C, VaxVac utilises vacuum storage to reduce the heat transfer between the vaccines and the surrounding environment. VaxVac has an aluminium outer covering with a thickness of 3mm, a height of 504mm, and a radius of 180mm, designed to withstand the vacuum pressure. The design has a valve on the top, which will be used by the hand pump so that the user can create a vacuum inside VaxVac.

Performance prediction methodology & performance predictions

Thermal Resistance

A thermal network was established for VaxVac which can be seen in **Error! Reference source not found.**. The thermal resistance network begins with the Outer Layer / External layer of the storage, where convection (R_{conv} (Outer Layer / External layer)) and radiation (R_{rad} (Outer Layer / External layer)) resistances are in parallel, representing heat transfer from the external environment (T_{source}) to the outer shell surface (T_{shell}). This is followed by conduction through the shell (R_{cond} (Shell)), connecting T_{shell} (outer) to the inner shell surface (T_{shell} (inner)).

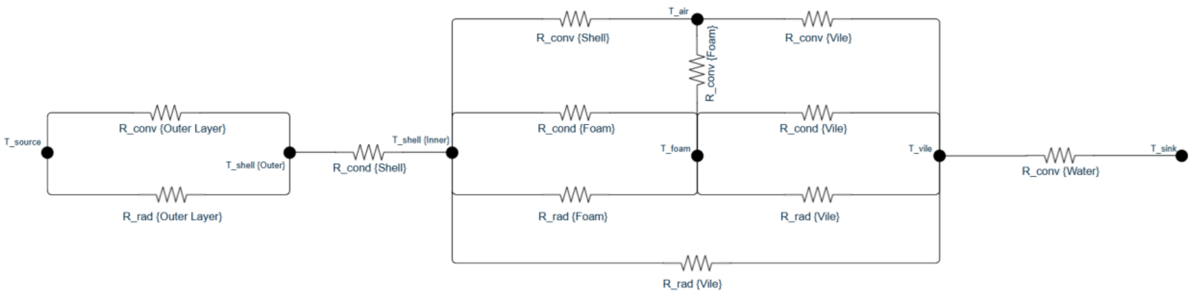

Figure 2: Thermal Network Diagram

From T_{shell} (inner), the heat flow splits into three parallel paths:

1. Path through the foam: This path includes conduction (R_{cond} (Foam)) and radiation (R_{rad} (Foam)) resistances in parallel, representing heat transfer from the inner shell to the foam (T_{foam}). From T_{foam} , heat flows to the vials (T_{vial}) via conduction (R_{cond} (Vial)) and radiation (R_{rad} (Vial)) resistances in parallel.
2. Path through the air: This path involves convection (R_{conv} (Shell)) from the inner shell to the internal air (T_{air}). From T_{air}, heat splits into two parallel sub-paths: one to the foam via convection (R_{conv} (Foam)), continuing to the vials as described above, and another directly to the vials via convection (R_{conv} (Vial)).
3. Direct radiative path: A direct radiative path (R_{rad} (Vial)) connects T_{shell} (inner) to T_{vial}, representing radiation between the inner shell and the vials.

Finally, heat flows from the vials (T_{vial}) to the water inside (T_{sink}) through a convection resistance (R_{conv} (Water)), which accounts for the combined effect of conduction through the vial walls and convection to the water.

$$R_{tot} = \left(\frac{1}{R_{conv,outer}} + \frac{1}{R_{rad,outer}}\right)^{-1} + R_{cond,shell} + \left(\frac{1}{R_{path1}} + \frac{1}{R_{path2}} + \frac{1}{R_{rad,shell-vile}}\right)^{-1} + R_{conv,water}$$

Where,

$$R_{path1} = \left(\frac{1}{R_{cond,foam}} + \frac{1}{R_{rad,foam}}\right)^{-1} + \left(\frac{1}{R_{cond,vial}} + \frac{1}{R_{rad,vial}}\right)^{-1}$$

$$R_{path2} = R_{conv,shell}\left(\frac{1}{R_{conv,vial}} + \frac{1}{R_{conv,foam} + \left(\frac{1}{R_{cond,vial}} + \frac{1}{R_{rad,vial}}\right)^{-1}}\right)^{-1}$$

Thermal conductivity, emissivity, and heat carrying capacity for the materials (shell, foam, and vials) are provided in Table 1, and the dimensions of the geometry, including the shell thickness {note that thickness here is referred as L which will be used in resistance calculation}, foam layer dimensions, and vial sizes, are detailed in Table 2.

Layers	Emissivity	Thermal Conductivity (W/m^2K)	Heat Carrying Capacity (J/kgK)	Density (kg/m^3)
Vial	0.9	1.2	830	2230
Foam	0.03	0.04	1400	10
Shell	0.3	273	880	2700
Reflective layer	0.01	-	-	-

Table 1: Properties of materials used

Layers	Height / Side length (m)	Radius (m)	Thickness (m)
Vial	0.008	0.03	0.001
Foam	0.05	0.177	0.177
Shell	0.18	0.177	0.003

Table 2: Geometric parameters

Analytical Estimation

The resistances for conduction, convection and radiation were calculated using following equations,

$$R_{cond} = \frac{L}{kA} \quad \left(\frac{K}{W}\right)$$

Where, L is the thickness of the layer, k is the thermal conductivity and A is surface area.

$$R_{conv} = \frac{1}{hA} \left(\frac{K}{W}\right)$$

Where, h is the heat transfer coefficient, and

$$R_{rad} = \frac{1}{\varepsilon_{eff}\sigma A({T_{source}}^2 + {T_{film}}^2)(T_{source} + T_{film})} \left(\frac{K}{W}\right)$$

Where ε_{eff} is the effective emissivity, σ is the Stefan-Boltzmann constant.

The heat transfer coefficient was derived by estimating Nusselt's Number (Nu) correlation for respective conditions.

$$h = \frac{Nu\,k}{L} \left(\frac{W}{m^2K}\right)$$

Here, L is the characteristic length which for simplicity was assumed as height.

$$Nu = 0.68 + \left(\frac{0.67Ra^{\frac{1}{4}}}{1 + \left\{\frac{0.492}{Pr}\right\}^{\frac{9}{16}}}\right)^{\frac{4}{9}}$$

Here, Pr is the Prandtl Number and Ra is the Rayleigh Number, which is estimated by,

$$Pr = \frac{\mu C_p}{k}$$

$$Ra = \frac{g\beta\Delta T L^3}{\upsilon\alpha}$$

Where μ is the Dynamic viscosity, g is the acceleration due to gravity, β is the coefficient of thermal expansion (K^{-1}), ΔT is the temperature difference, υ is the kinematic viscosity (m^2/s) ,and α is the thermal diffusivity (m^2/s). Detailed estimates and calculations are provided in Appendix A1. Final values for resistance can be seen in **Error! Reference source not found.**Table 3.

Table 3: Estimated Thermal Resistance

Resistance	Value (W/m^2K)
R_{conv}, ext	4.15550391
R_{conv}, shell	41682.8177
R_{conv}, foam	32639.44264
R_{conv}, vial	80568.02789
R_{conv}, water	0.145488053
R_{rad}, ext	26.78578524
R_{rad}, foam	9.824685273
R_{rad}, shell-vial	0.948801382
R_{rad}, foam-vial	7.213827867

R_{cond}, shell	1.79934E-05
R_{cond}, foam	5.834512147
R_{cond}, vial	0.002712252

With these values estimated temperature after 10 hrs was at 3.4557 °C when initial temperature was assumed to be 2 °C. The temperature was approximated using a lumped capacitance model, assuming the vaccine chamber internals are a single "lump" with negligible temperature differences between each point of the lump. With following equation was used to calculate the internal temperature as a function of time, with an initial temperature of 2 °C.

$$T = T_{source} + (T_{initial} - T_{source}) \cdot e^{-\frac{U \cdot A_{internal}}{V_{internal} \cdot \rho \cdot C_p} \cdot t}$$

Where T_{source} is the environmental temperature set at 35 °C, U is the overall heat transfer coefficient of the system in W/m^2K, $A_{internal}$ is the surface area of the internal vaccine chamber in m^2, $V_{internal}$ is the internal vaccine chamber volume in m^3, ρ is the density of the vaccine in kg/m^3, Cp is the heat capacity of the vaccine in J/kgK, and t is time in seconds.

CFD Simulation Setup

Governing Equations

The governing equations solved in SolidWorks Flow simulation are the Reynolds-averaged Navier-Stokes equations. These equations describe the conversation of mass and momentum for a fluid flow. This section outlines the generalised form of the governing equations of conservation of mass, momentum and energy. The software employs the finite volume method to discretize and solve these equations. The k-ε turbulence model is employed to approximate turbulent effects and can also handle heat transfer through conduction, convection, and radiation.

Continuity Equation

$$\nabla \cdot \vec{v} = 0$$

Where $\vec{v}$ represents the velocity vector field.

Momentum Conservation

The

$$\frac{\delta(\rho\vec{v})}{\delta t} + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla P + \nabla \cdot (\bar{\tau}) + \rho\vec{g} + \vec{F}$$

Where $\frac{\delta(\rho\vec{v})}{\delta t}$ represents the rate of change of momentum per unit volume. $\nabla \cdot (\rho\vec{v}\vec{v})$ represents the convection transport of momentum, ∇P represents the pressure gradient force, $\nabla \cdot (\bar{\tau})$ represents viscous stress tensor term which accounts for internal friction and $\rho\vec{g} + \vec{F}$ represent gravitational and body forces.

Energy Equation

$$\frac{\delta(\rho e_0)}{\delta t} + \nabla \cdot \left(\vec{v}(\rho e_0 + P)\right) = \nabla \cdot (k_{eff}\nabla T + (\bar{\tau} \cdot \vec{v}))$$

Where $\frac{\delta(\rho e_0)}{\delta t}$ represents the rate of change of internal energy of the fluid with respect to time. e_0 is the internal energy of the fluid, P represents the pressure work term, $k_{eff}\nabla T$ represents the conduction term where k_{eff} is the thermal conductivity. $\bar{\tau} \cdot \vec{v}$ represents the work done by viscous stresses.

General Settings

The geometry for the vaccine cooler was created in SOLIDWORKS and imported into Flow Simulation. In general settings Fluid Flow, Radiation, and Gravity are activated. Air was selected as the working fluid with the standard Flow Simulation fluid properties. Ambient initial conditions of pressure and temperature were set to 10kPa and 275.15K. Turbulence intensity was 5% and length was 0.001m. An internal domain was chosen for the analysis type. The analysis type was set to ‘Transient’. It was decided to use a timestep of 10s to balance simulation accuracy and speed. The total simulation time was set to 36000s. This allows for the final temperature of the vials to be found at 10 hours.

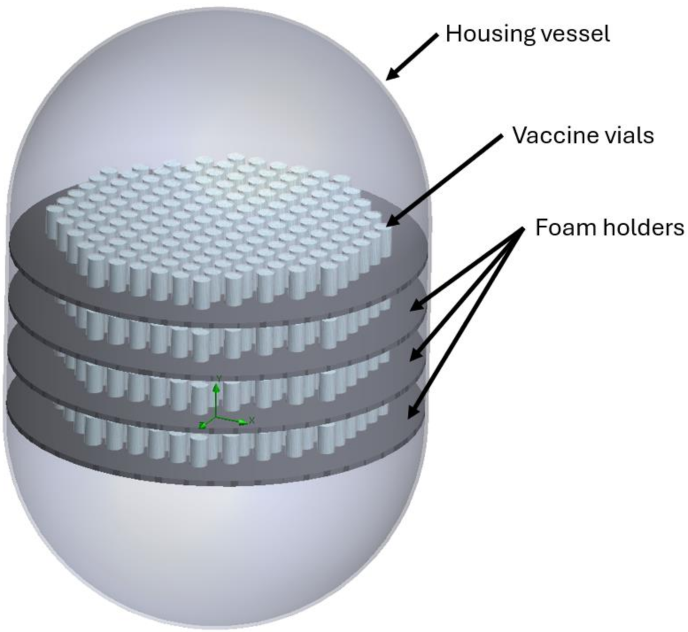

Figure 3: Modelled Geometry

The geometry was simplified for the simulation, omitting handles, latches, and the pump inlet. The aluminium outer housing was modelled around four layers of UF foam vial holders. Each layer has 156 vials, totalling 624 vials.

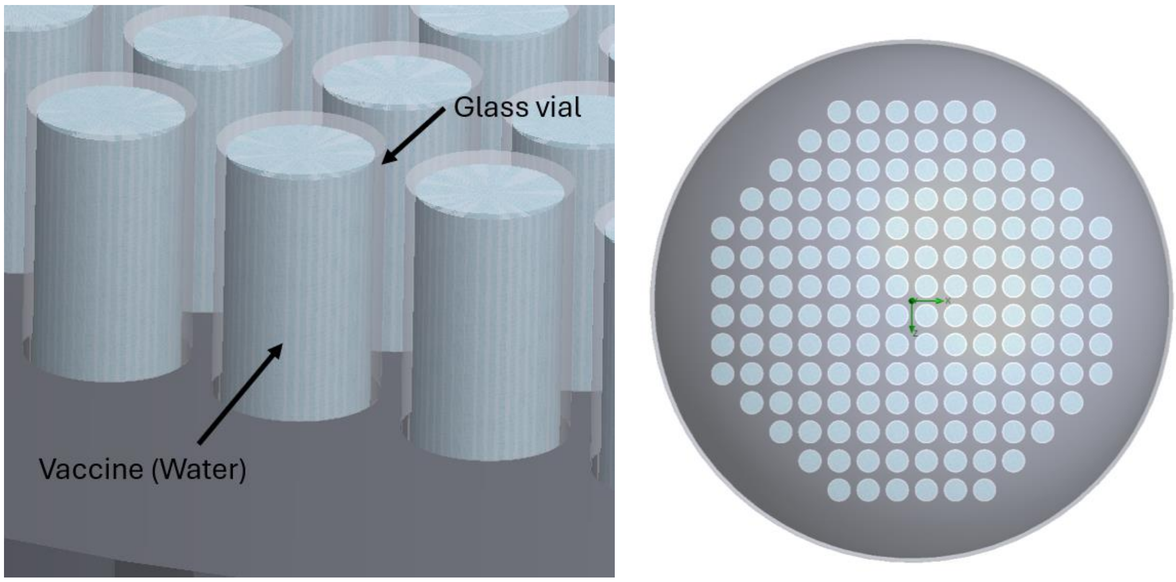

Figure 4: Vial Geometry and Arrangement

The vials are geometrically simplified to minimize meshing complexity and computational resource demands. The cylindrical shape and uniform wall thickness excessively fine mesh resolution.

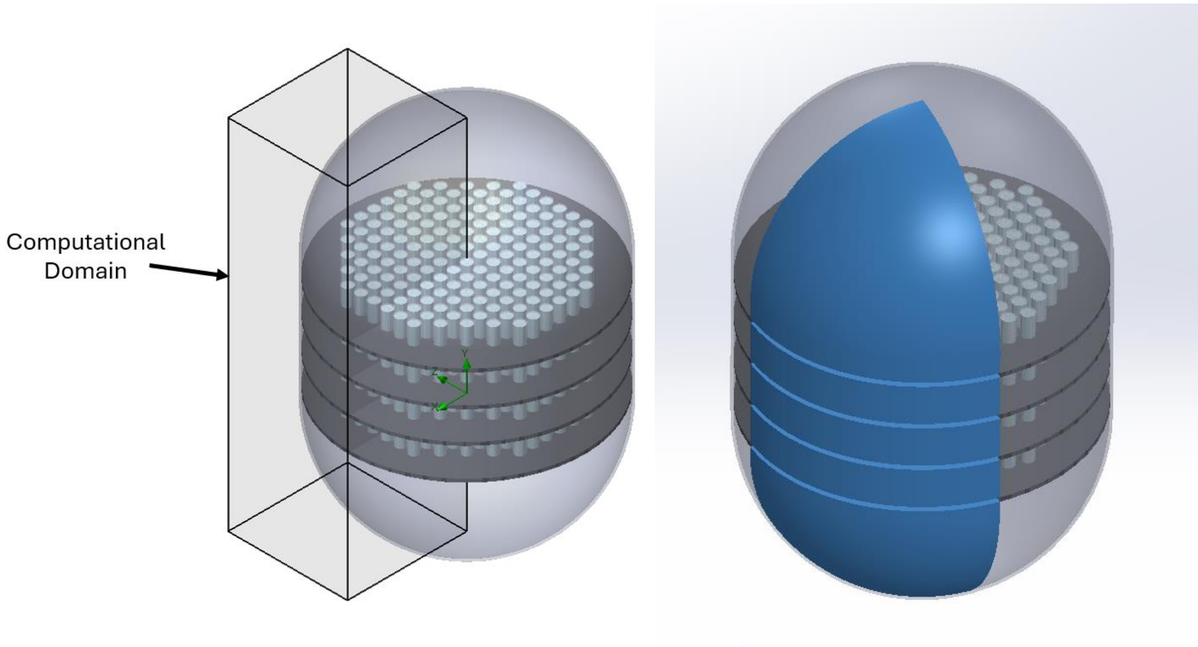

Figure 5: Computational and Fluid Domains

The vials were arranged in such a manner that there will be no flux across two axes. This enables two symmetry conditions which reduces computation time by a factor of four.

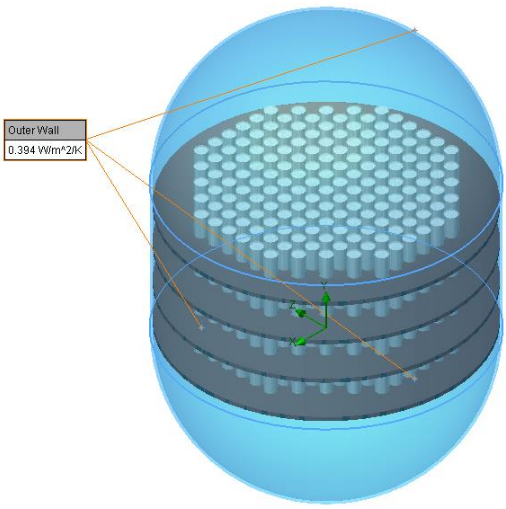

Figure 6: Outer Wall Boundary Condition

An outer wall heat transfer coefficient of 0.394W/m^2K has been applied to all outer surfaces. This value was taken from the analytical calculations as explained above. The temperature of this boundary condition is set to 35°C, of ambient temperature specified in the design brief. The heat transfer coefficient was estimated using the above equations and can be seen in Appendix A1.

Meshing and Mesh Independence

A mesh independence study was conducted to ensure that the results were not influenced by the mesh resolution. The final geometry obtained from the analytical calculations was used. The external fluid temperature was set to 308.2K, the convective heat transfer coefficient to 0.394 W/m^{2}K, and the internal pressure to 10kPa. As with the final simulations, the highest vial temperature was used as the simulation goal. As with the final simulations, the global mesh encompasses the entire computational domain. The value was varied between 2 and 6 for the mesh independence study, with the Minimum Gap Size set to a value of 0.01 m. Two local meshes were used to increase the refinement around the area of the vials. The larger of the two included the entire foam area, and the smaller one contained only the area with the vials and the adjacent outer wall. This setup was used to allow for more precise calculations in these areas, which were expected to have higher temperature gradients, without increasing the overall computational time by an unreasonable amount. A sample of Mesh 4 is shown in Figure 7 to clearly illustrate in which regions the mesh is more refined.

The results are tabulated below in Table 4. A comparison of the highest and lowest vial temperature with mesh cell count is graphed in Figure 8.

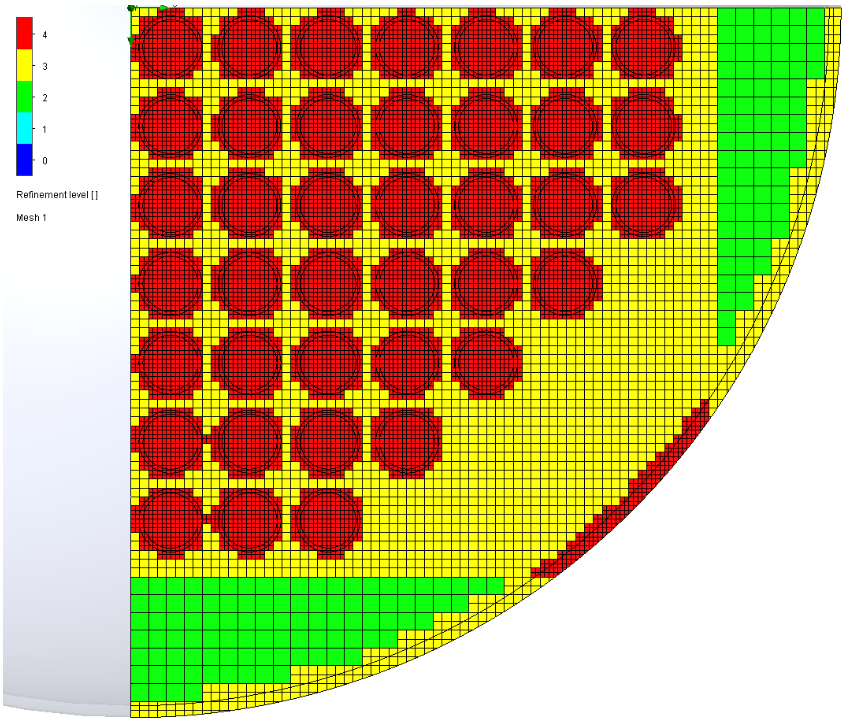

Figure 7: Sample Mesh 4 with Local Mesh Refinement

Table 4: Mesh Independence Study Results

Mesh Level	Total Mesh Cell Count	Vial Temperature [K]	Error [%]	Run Time [min]
1	**38293**	**4.649**		3
2	**59304**	**5.019**	7.372	7
3	**131043**	**5.196**	3.406	16
4	**225493**	**4.956**	4.843	40
5	**504313**	**5.032**	1.510	83
6	**1103029**	**5.056**	0.475	192
7	**2854031**	**5.043**	0.258	531

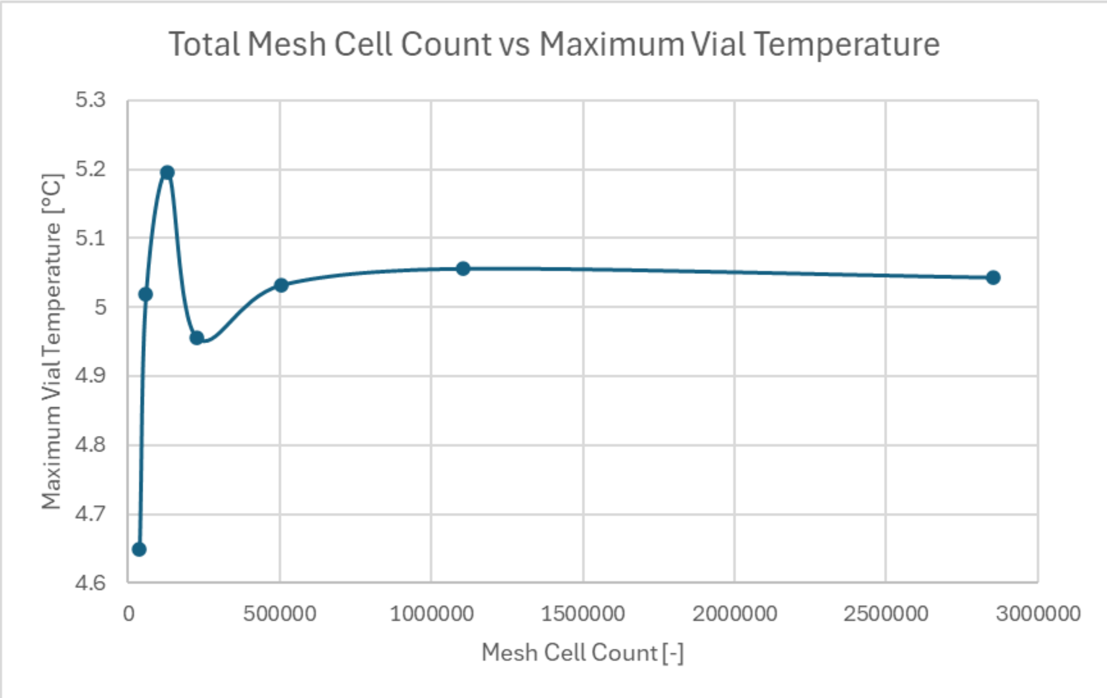

Figure 8: Mesh Independence Study Results of Maximum Vial Temperature Parameter

Although the vial temperature value shows clear oscillations for the less refined meshes, as the cell count increases, the mesh can be considered converged. Due to the increasingly large computational requirements, Mesh 5 was ultimately chosen as it showed the best balance of accuracy and run time. Although the mesh has not fully converged at this point, the percentage error of 1.5% was considered acceptable given the time constraints.

Simulation Model Verification and Results

Temperature cut plots are used to assess the results of the CFD study. The vacuum space causes a reduction in convection efficiency as designed. However, this results in radiation and conduction becoming more significant. This informed the decision to reduce the UF foam 'holder' thickness to 5mm from its original of 30mm.

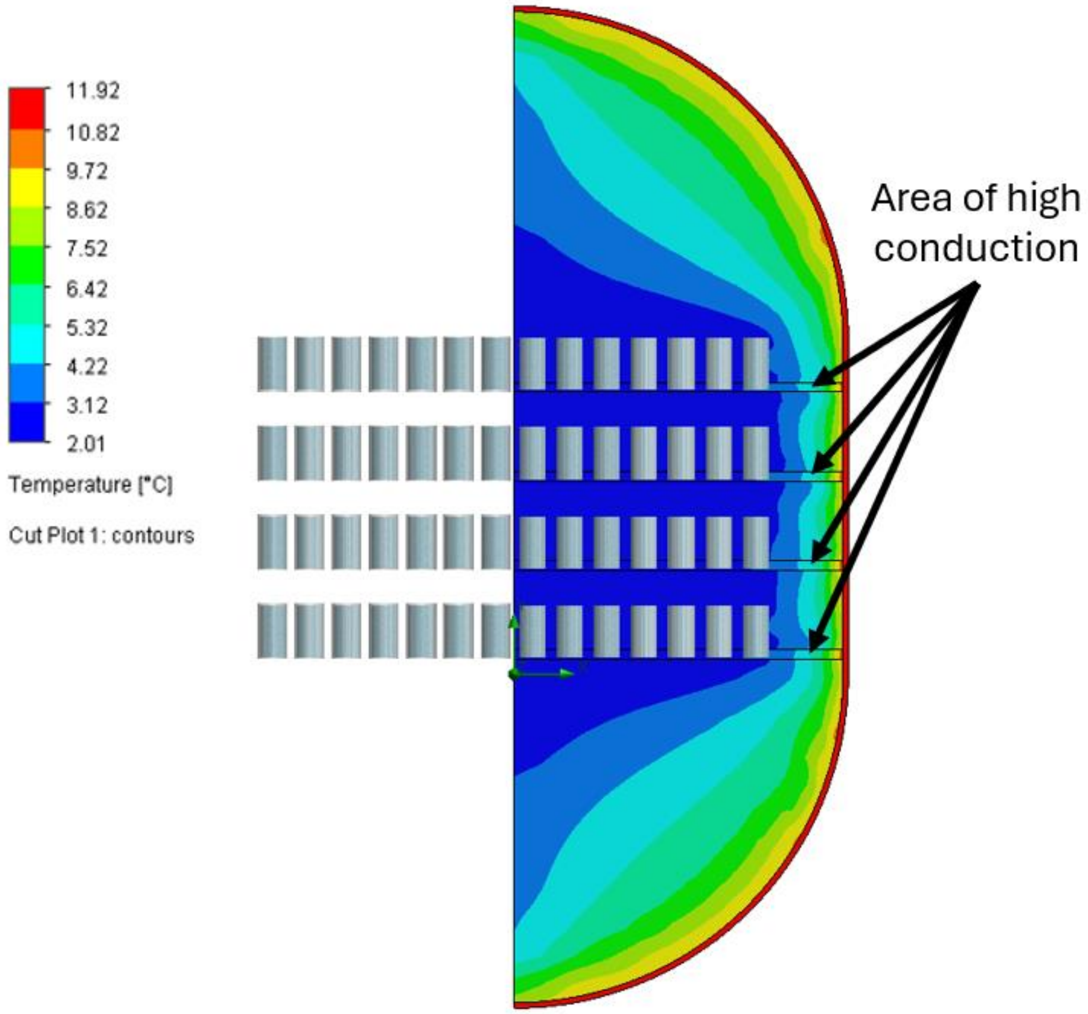

Figure 9: Front plane temperature contour plot

The thermal mass of the vaccines results in each vial absorbing relatively small amounts of heat and the arrangement of the vials limits the direct exposure of the inner vials to outside heat sources.

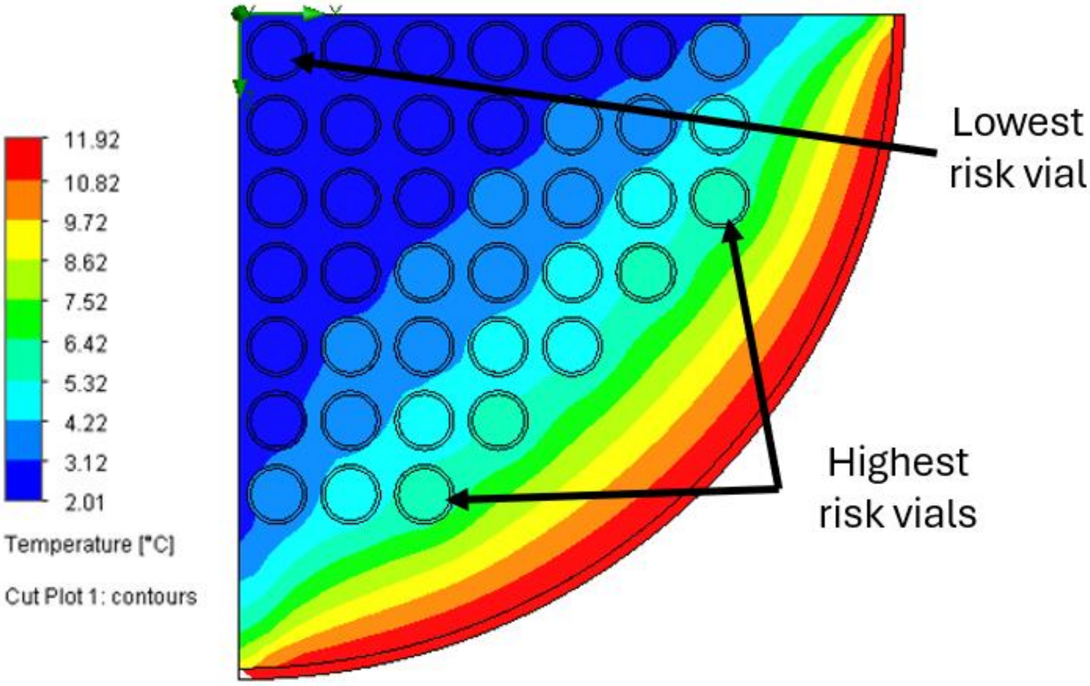

Figure 10: Top view temperature contour plot

The water in the outer high-risk vials and the inner low-risk vial were assigned temperature point goals. After 10 hours, the high-risk vials recorded temperatures of 5.73°C and 5.71°C. The low-risk vial recorded a temperature of 2.10°C. The global average temperature of the cooler was 6.86°C and the solid average temperature was 6.18°C. Overall, the average vaccine temperature was 4.51°C after 10 hrs.

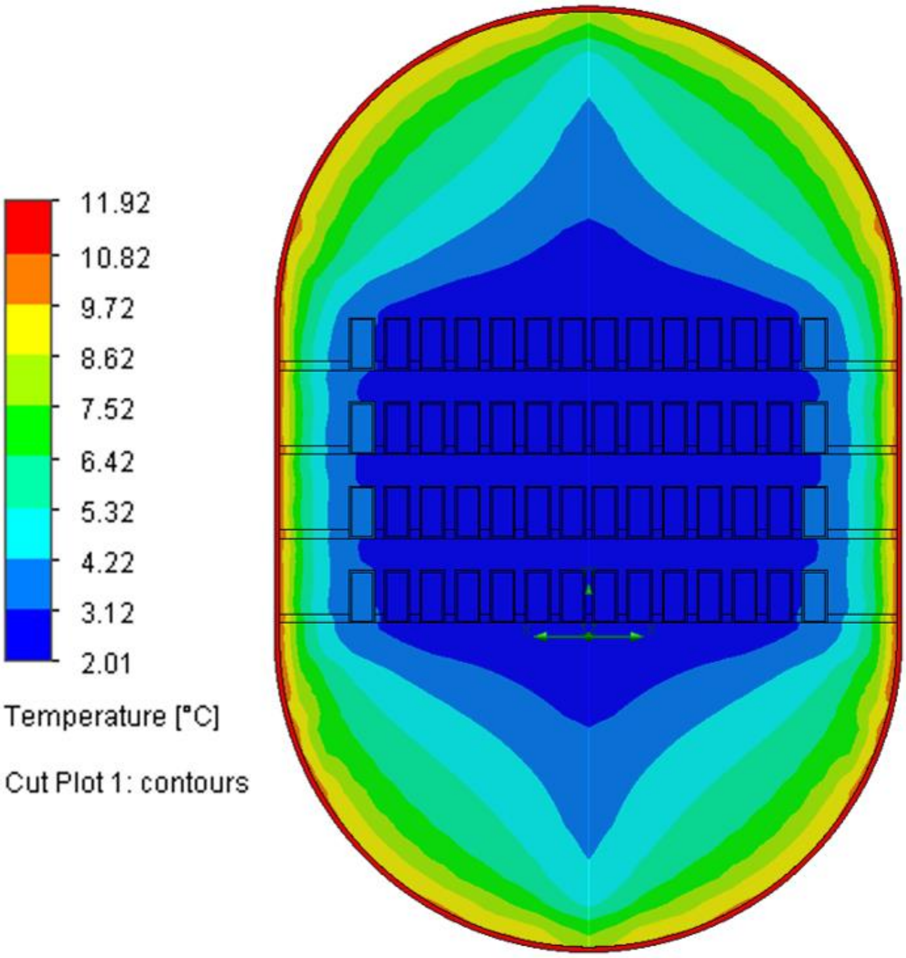

Figure 11: Mirrored temperature plot

Most vaccines are maintained well below the upper threshold of 8°C which is crucial for vaccine efficacy. The vaccines on the peripheral are warmer but still below the threshold temperature.

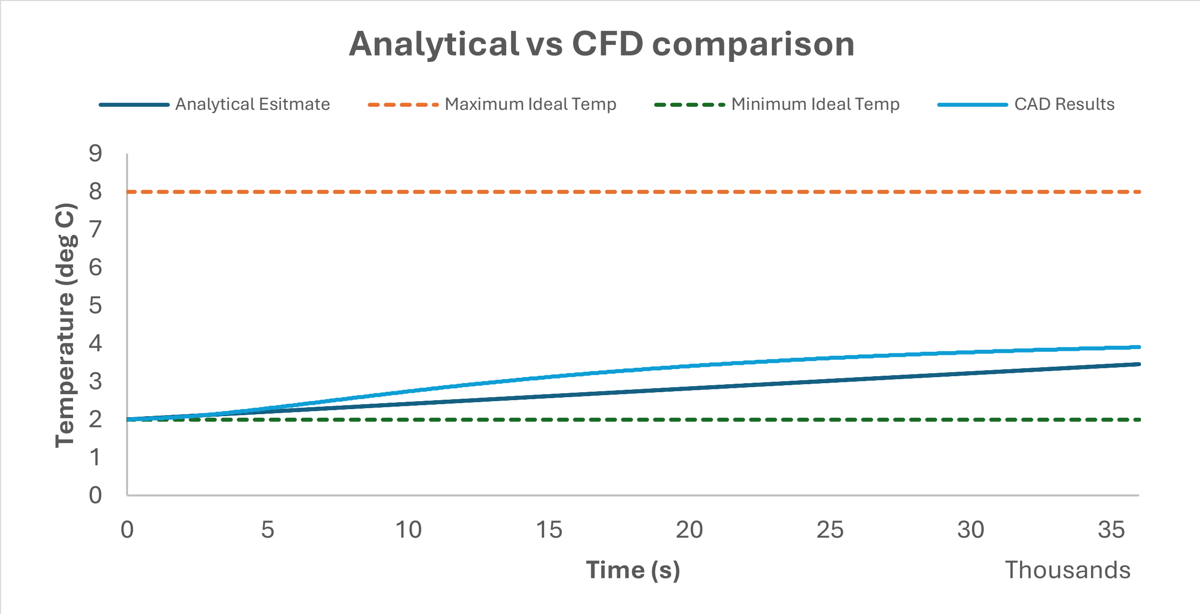

Figure 12: Comparison of analytical and numerical temperature data

The numerical data from the simulation was also compared with the lumped capacitance analytical data. Overall, the agreement between analytical and numerical is strong given the limitations of each approach to simulating the real case. The curve in the estimates is most probably due to the lumped capacitance equation, where it was assumed overall heat coefficient, density, and heat carrying capacity as constants, which will be dynamic as temperature changes. The effect can be big depending on the pressure and temperature which is seen here.

Design for Manufacture

Materials and Manufacturing

The shell is CNC machined and divided into two parts (top cover and main body), with a hollow interior and a wall thickness of 3mm to ensure the overall structural strength and minimise weight. The hinge and latch connections between the top cover and the main body are of common sizes on the market, which are easy to purchase and replace.

The backpack structure is assembled via a number of different techniques: the straps all adopt the standard universal backpack fasteners, which make connecting and adjusting straps hassle-free. The shoulder straps and cushioning can be made via standardised sewing processes which can be mass-produced in countries such as Vietnam where labour costs are relatively low. For the bottom support frame, aluminium alloy bracket is used, which is uses conventional CNC and bending/cutting methods. For the back panel, low cost ABS is used for its availability, recyclability and structural properties. This can be moulded in one piece thanks to injection moulding to provide good structural support.

Bill of Materials (BOM)

The total material costs for this design are presented in the form of components as shown in Table 5 below:

Table 5: Bill of Materials and Cost

Materials or Components	**Unit Cost [€]**	**Quantity**	**Total Cost [€]**
Shell (Aluminum Alloy 6061-T6)	88	1	88
Sealing Ring (Lid area)	4.52	1	4.52
One-Way Valve (Top)	0.4	1	0.4
Hinge Connector	0.5	1	0.5
Backpack Frame	23.8	1	23.8
Total			117.22

Pricing and Price Point

There are several vaccine coolers on the market today, such as the vericormed vaccine coolers[1], which typically cost between €500 and €1500, depending on the capacity, insulation, and whether they have an active cooling system or not. For example, the Cool Cube™ series (e.g., Cool Cube™ 03 at Refrigerator Temps or Cool Cube™ 08 at Refrigerator Temps), which uses Vips[2] and PCM[3] materials, is priced between €500 and €750. In contrast, our current design is priced between €500 and €1500, depending on the capacity and whether or not it has an active cooling system.

Figure 13: Cool Cube™ 28 at Refrigerator Temps [4]

In contrast, our design is a lightweight, backpack-type structure that offers greater portability and ergonomics. The whole machine is made of CNC-machined aluminium shell, sandwich insulation design (including PTFE[5]), and integrated one-way valve hole for pressure adjustment. The modular design of the backpack structure combines hand-stitched shoulder straps, EVA cushioning, an injection-moulded ABS back panel, and a CNC-machined aluminium alloy chassis, giving the product both good temperature control and a sense of comfort and style in mobile scenarios.

Figure 14: Our designed module

As the design involves more medium and high-end processing technology (such as CNC, injection moulding, sewing, etc.), as well as higher user experience orientation, its product positioning is between traditional passive refrigerator and high-end active refrigeration equipment. Priced in the €250 range, the product is extremely competitive in the current market. Since it uses a more reliable and stable thermal insulation method, without having to worry about the lifetime of the cooling/insulation materials (PCM, VIPs), it provides a novel and interesting product.

Technology Appropriateness and Outlook

The VaxVac design demonstrates significant potential in reducing vaccine wastage and improving healthcare delivery in extreme conditions. By combining advanced thermal resistance modelling with practical manufacturing techniques, the system achieves efficient temperature regulation while remaining portable and user-friendly. Simulation results confirm its ability to maintain vaccines below the critical threshold of 8°C, even under prolonged exposure to high ambient temperatures.

While challenges such as manufacturing scalability and long-term durability remain, the project's analytical foundation and innovative approach position it as a transformative solution for vaccine logistics. With funding from investors and philanthropic organizations, VaxVac could play a pivotal role in ensuring global vaccine accessibility and efficacy, particularly in underserved regions.

Refences

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[5] R. Wang, G. Xu, and Y. He, ‘Structure and properties of polytetrafluoroethylene (PTFE) fibers’, E-Polym., vol. 17, no. 3, pp. 215–220, May 2017, doi: 10.1515/epoly-2016-0059.

Appendix

A1.1 Hand Calculation

Error! Reference source not found. shows the thermal network diagram with multiple nodes and Figure 1215 shows the heat flow taking place through the circuit. To estimate the overall resistance, the first heat transfer coefficient was derived from Nu. It was considered that there were 600 vials placed and 4 sheets of Foam to hold the vials.

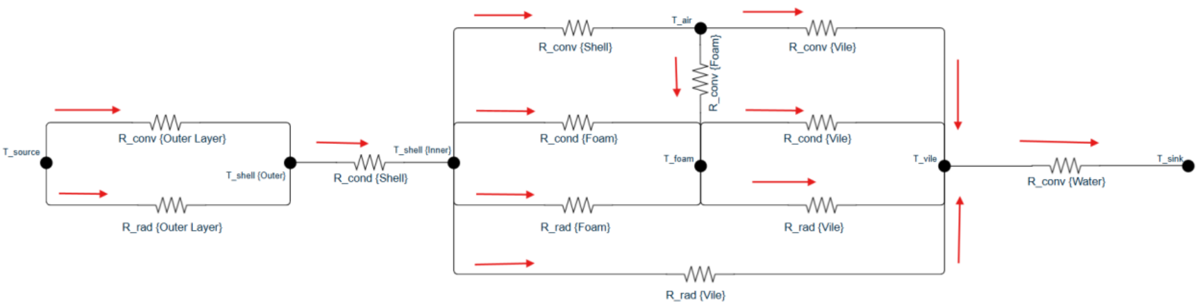


Figure 1215: Thermal Network Diagram with heat flow

$$T_{film} = \frac{T_{source} - T_{sink}}{2} = 18.5\ ℃$$

Thus, for this temperature of air following parameters were estimated,

Air Properties		
Parameters	***Values***	***Unit***
Heat Carrying Capacity	1006.00000	J/kgK
Density	1.21870	kg/m^3
Volumetric coefficient of thermal expansion (β)	0.05405	K^{-1}
Dynamic Viscocity	0.00002	Pa·s
Kinematic Viscosity	0.00001	m^2/s
Thermal Conductivity	0.02561	W/m
Prandal Number	0.70555	-
Thermal Diffusivity	0.00002	m^2/s
A^{ccn} due to Gravity	9.81	m/s^2

Table 6: Air Properties at Film Temp

Thus, Rayleigh Number, Nusselt Number and HTC comes to be

$$Ra = \frac{9.81 * 0.05405 * (308 - 291.5) * 0.537^3}{0.0001 * 0.0002} = 4472866967$$

$$Nu = 0.68 + \left(\frac{0.67 * 44728669967^{\frac{1}{4}}}{1 + \left\{\frac{0.492}{0.70555}\right\}^{\frac{9}{16}}} \right)^{\frac{4}{9}} = 8.2618$$

$$h = \frac{8.2618 * 0.00001}{0.537} = 0.394 \left(\frac{W}{m^2 K}\right)$$

Film temperature was assumed to be average of the source and sink temperature as thickness of shell was low and there are not enough layers in between to cause different film temperatures at different locations.

As SolidWorks cannot simulate a perfect vacuum, and it is not humanly possible to create a perfect vacuum, the pressure was assumed to be at 10 kPa, thus, there will be a slight amount of air, which will cause convection between air and other components inside the storage. To estimate the HTC for air at low pressure, the Ideal Gas Law was used to estimate the properties such as density, Sutherland's Equation to get dynamic viscosity, and an empirical relation to get thermal conductivity, and finally kinematic viscosity and thermal diffusivity were calculated normally by standard equations.

$$\rho = \frac{P}{R * T_{film}} \left(\frac{kg}{m^3}\right)$$

$$\mu = \mu_{ref} \left(\frac{T_{film}}{T_{ref}}\right)^{\frac{3}{2}} \left(\frac{T_{ref} + S}{T_{film} + S}\right) \ (Pa \cdot s)$$

Where S is Sutherland's constant (K) and is approx. 110.4 K for air

$$k = k_0 \left(\frac{T_{film}}{T_{ref}}\right)^n$$

Where n is approx. 0.76 for air. Once the important parameters were obtained, following were the values,

Air Properties at low pressure		
Pressure	10000	**Pa**
R	287	**J/kgK**
Parameters	***Values***	***Unit***
Heat Carrying Capacity	1006.00000	J/kgK
Density	0.11953	kg/m^3
Volumetric coefficient of thermal expansion (β)	0.05405	K^{-1}
Dynamic Viscosity	0.0000008	Pa·s
Kinematic Viscosity	0.00001	m^2/s
Thermal Conductivity	0.00289	W/m

Prandtl Number	0.26826	-
Thermal Diffusivity	0.00002	m^2/s
A^{ccn} due to Gravity	9.81	m/s^2

Table 7: Air Properties at Low Pressure

With these values, Nu was 0.95591145 and h was 1.3705*10^-06 W/m^2K, respectively. The same equations were used for water stored in vials as well, because there was no flow taking place, removing dependency of Reynolds Number, thus Nu was estimated to be 27.13325215 and h was 28.31103082 W/m^2K. Thus, all the values can be seen below

Outer Air		Water		Low Pressure Air	
Nu	HTC (W/m^2K)	Nu	HTC (W/m^2K)	Nu	HTC (W/m^2K)
8.262	0.394	27.133	28.311	0.956	1.3705E-06

With these values we will get convective resistance i.e.,

$$Rconv, ext = \left(\frac{1}{hA}\right) = \left(\frac{1}{0.394 * 0.6107}\right) = 4.156 \ \left(\frac{K}{W}\right)$$

Conductive resistance was straight forward,

$$Rcond, shell = \left(\frac{L}{kA}\right) = \left(\frac{0.003}{273 * 0.6107}\right) = 1.79E - 05 \ \left(\frac{K}{W}\right)$$

Similarly for radiation,

$$Rrad, ext = \frac{1}{\varepsilon\sigma A({T_{source}}^2 + {T_{film}}^2)(T_{source} + T_{film})} = 26.786 \ \left(\frac{K}{W}\right)$$

Thus, from the previous equations discussed in the Analytical Estimation section, total resistance appeared to be 4.497 K/W. Thus, the overall heat coefficient is inverse of the total resistance multiplied by area, which shows overall HTC is 0.3642 W/m^2K. And with lumped capacitance model, following was the result

$$T = 308 + (275 - 308) \cdot e^{-\frac{0.3642*0.6107}{0.0409*999.9*4215.04}\cdot 36000} - 273 = 3.456 \ (°C)$$

A1.2 Initial Design

The initial idea was planned to be a simple rectangle which was supposed to have inner rubber layer for insulation, Aerogel as a second layer to increase overall resistance, Vacuum insulated panels as a third layer, and Aluminium reflector as the final layer to reflect most of the heat. The estimated temperature after 10 hrs was 7.16 °C which can be seen in Figure 1316.

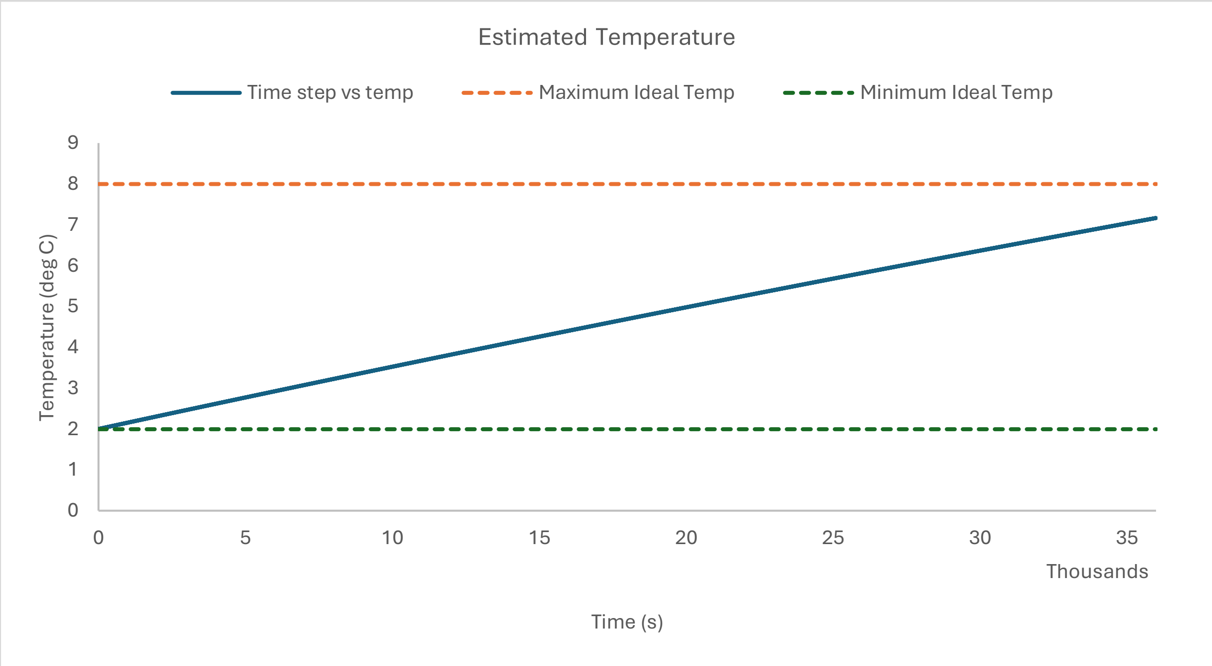


Figure 1316: Initial Design

The issue with the current design was expensive products such as VIPs and Aerogel, which bring up high upfront costs and were not feasible. Later, the design was simplified, and it was decided to go with the storage unit which is completely vacuum. The thermal network diagram for this model can be seen in the following Figure 1417.

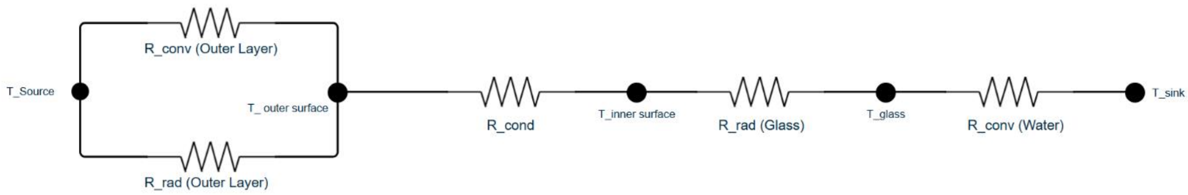


Figure 1417: The Old Thermal Network Diagram with a perfect vacuum and no foam was ignored which was used to hold the vials

With this network, as the vacuum created was perfect, the convection heat loss was ignored, and as foam was also ignored for model simplicity, there was no conduction between vials and shell. Overall thermal resistance was 1.376 K/W and the max temp after 10 hrs for 600 vials was 4.092 °C. Results can be seen in the following Figure 15: 18.

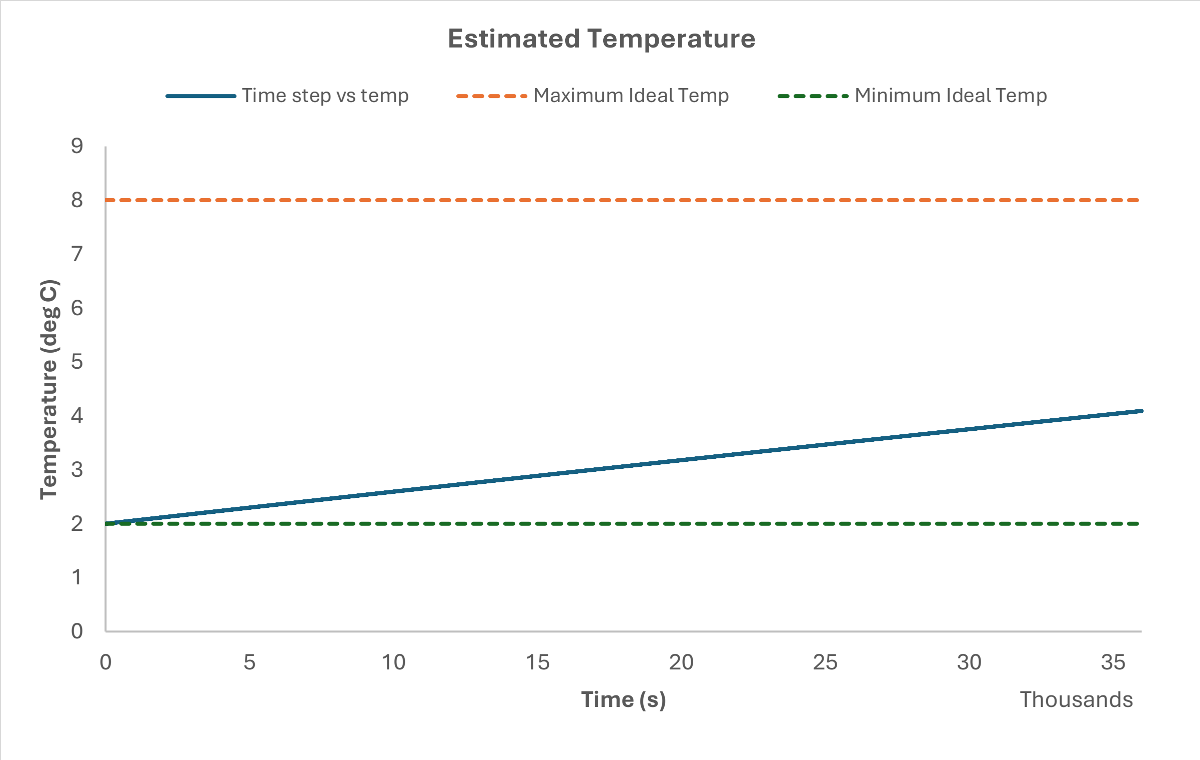


Figure 15: 18Version 2 of Cool box

A1.3 Simulation Images

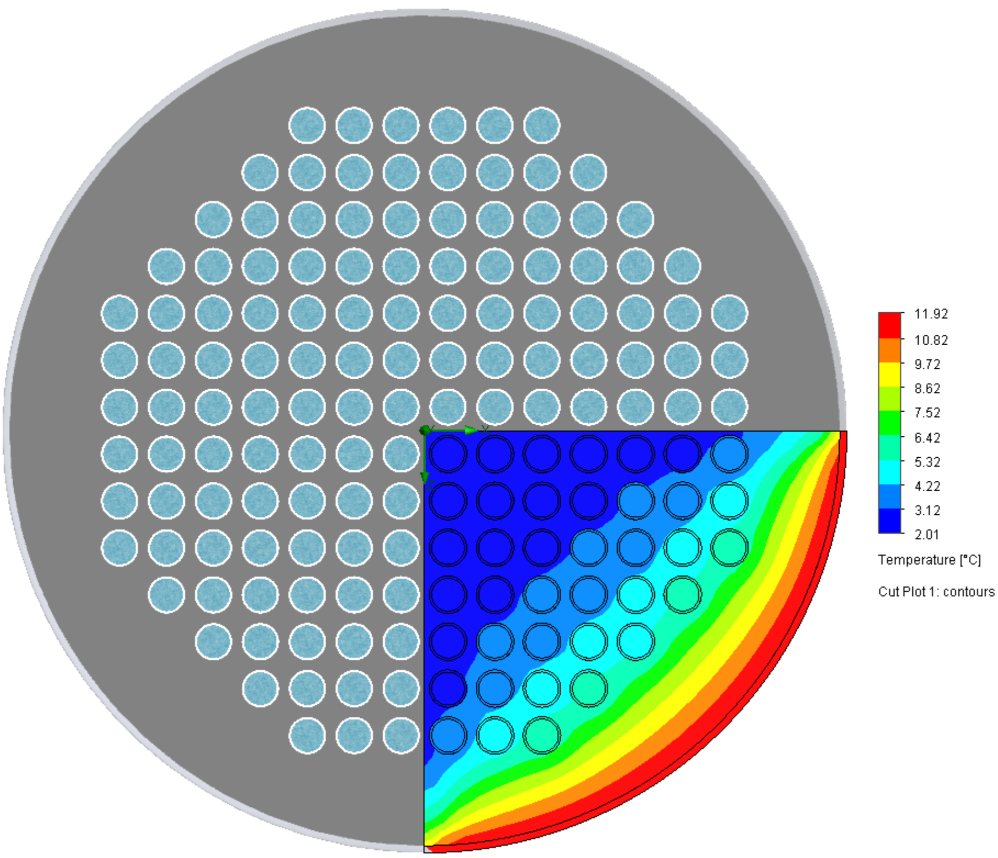


Figure 16: Top view simulation

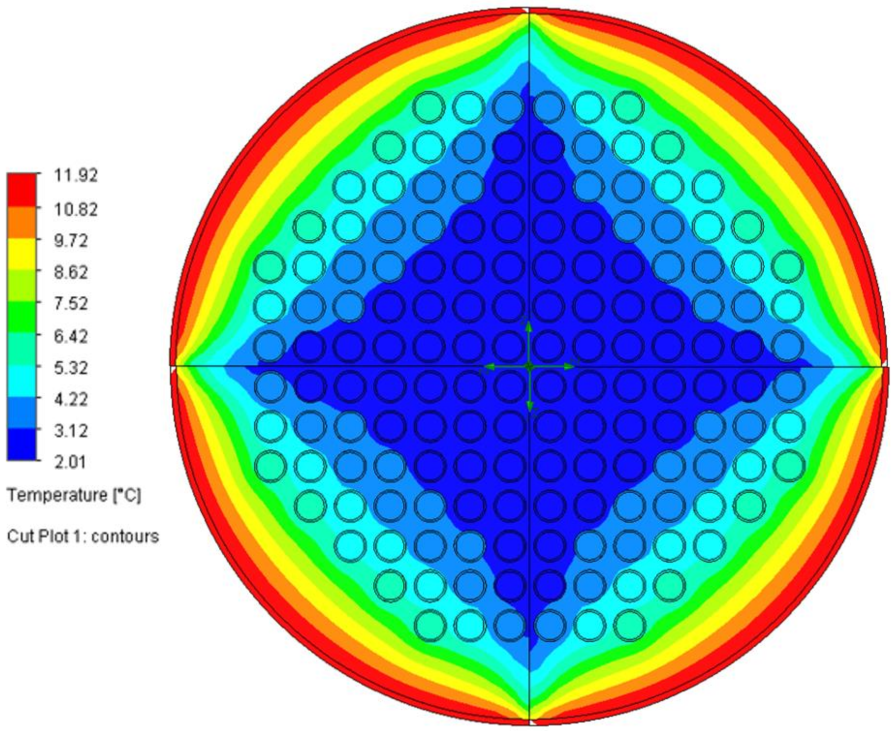


Figure 17: Top view symmetrical simulation

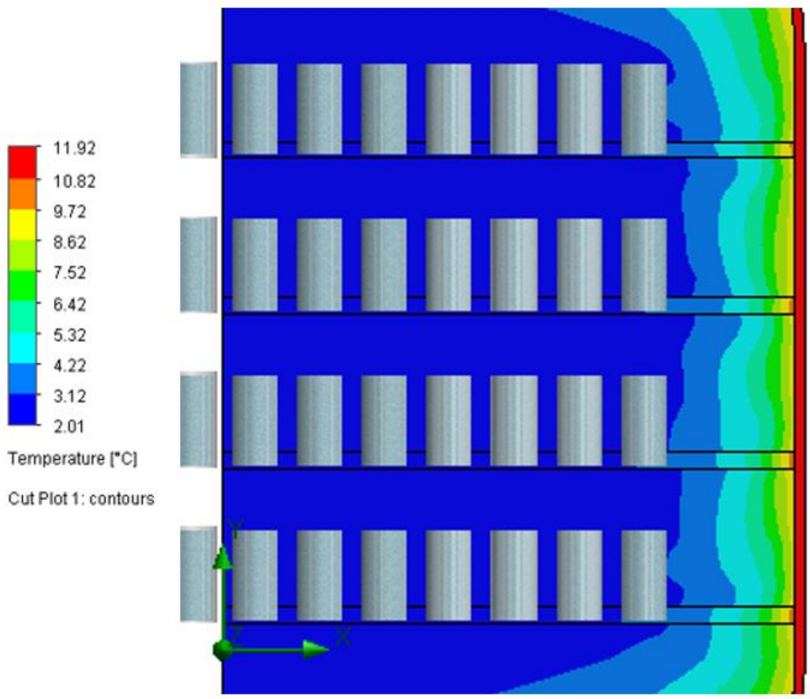


Figure 18: Side view simulation

A1.4 Renders

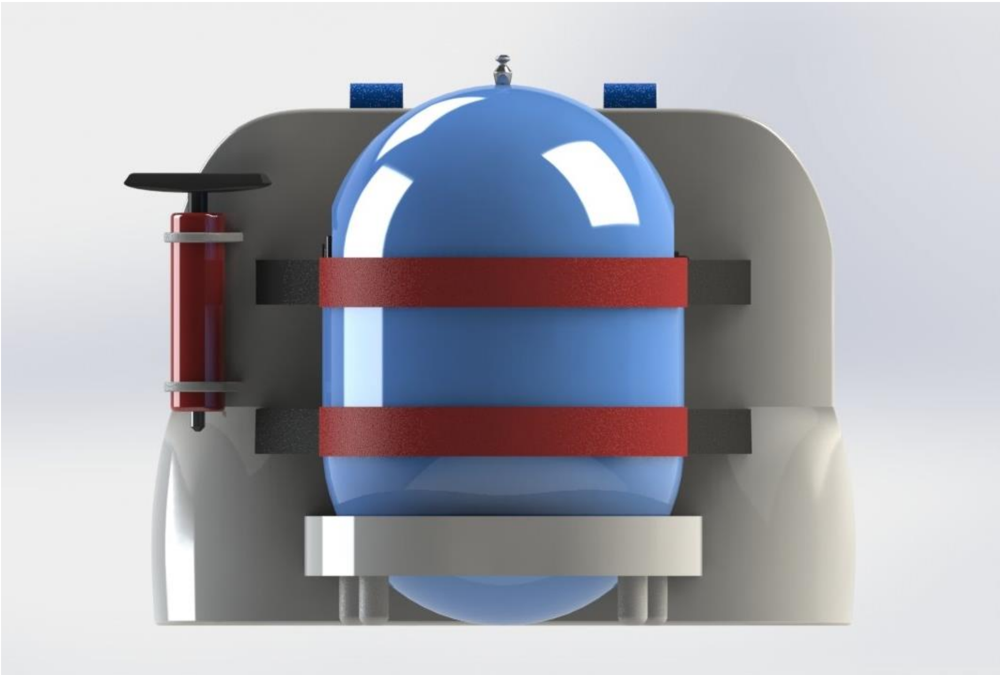


Figure 19: Back view

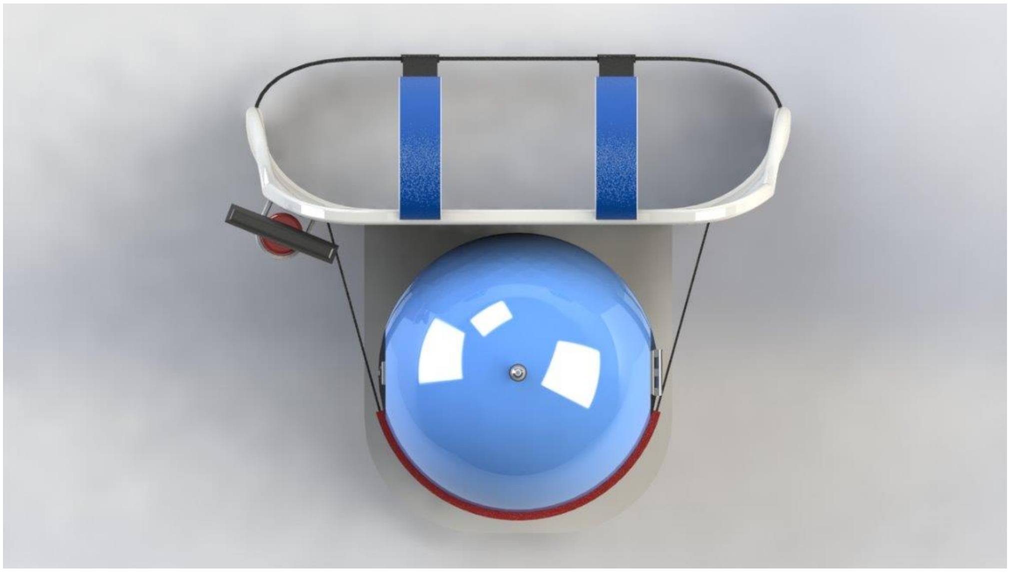


Figure 20: Top view

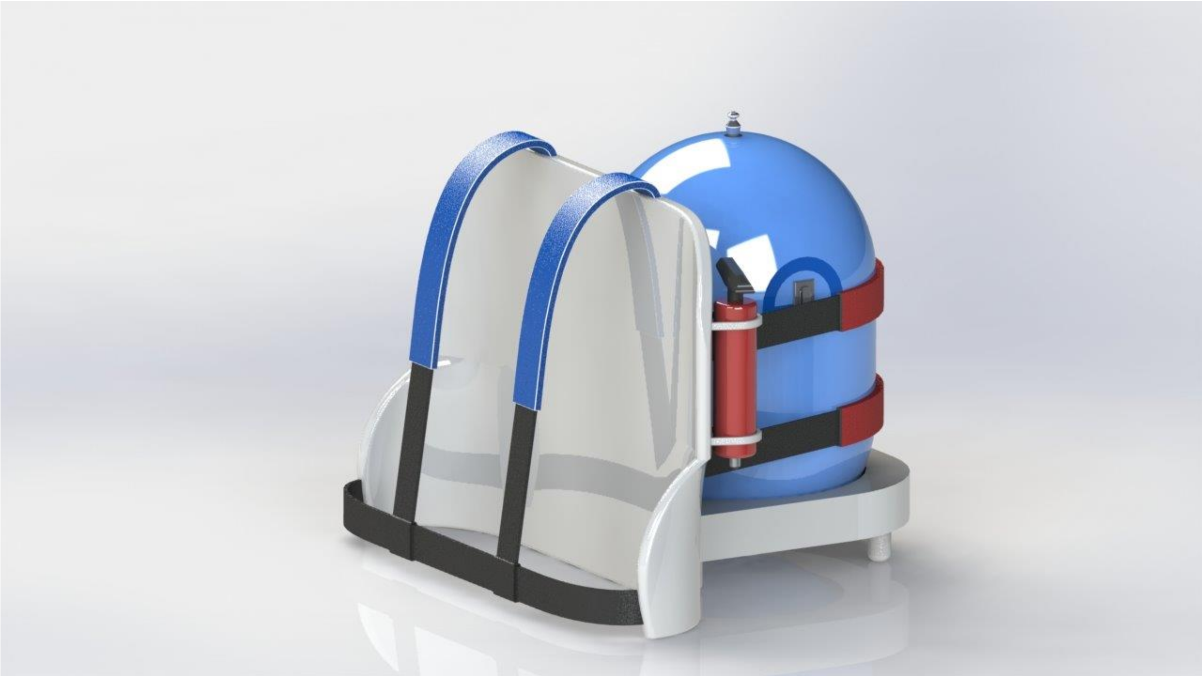
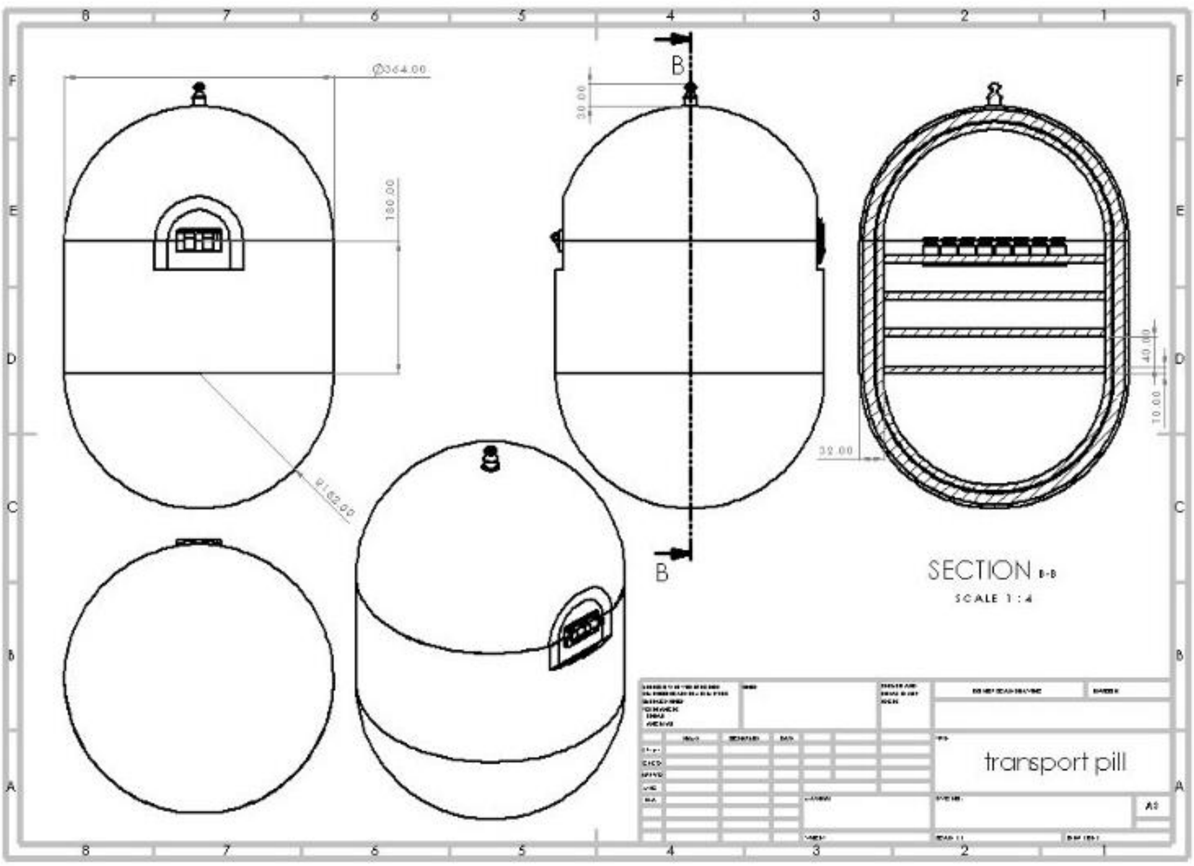


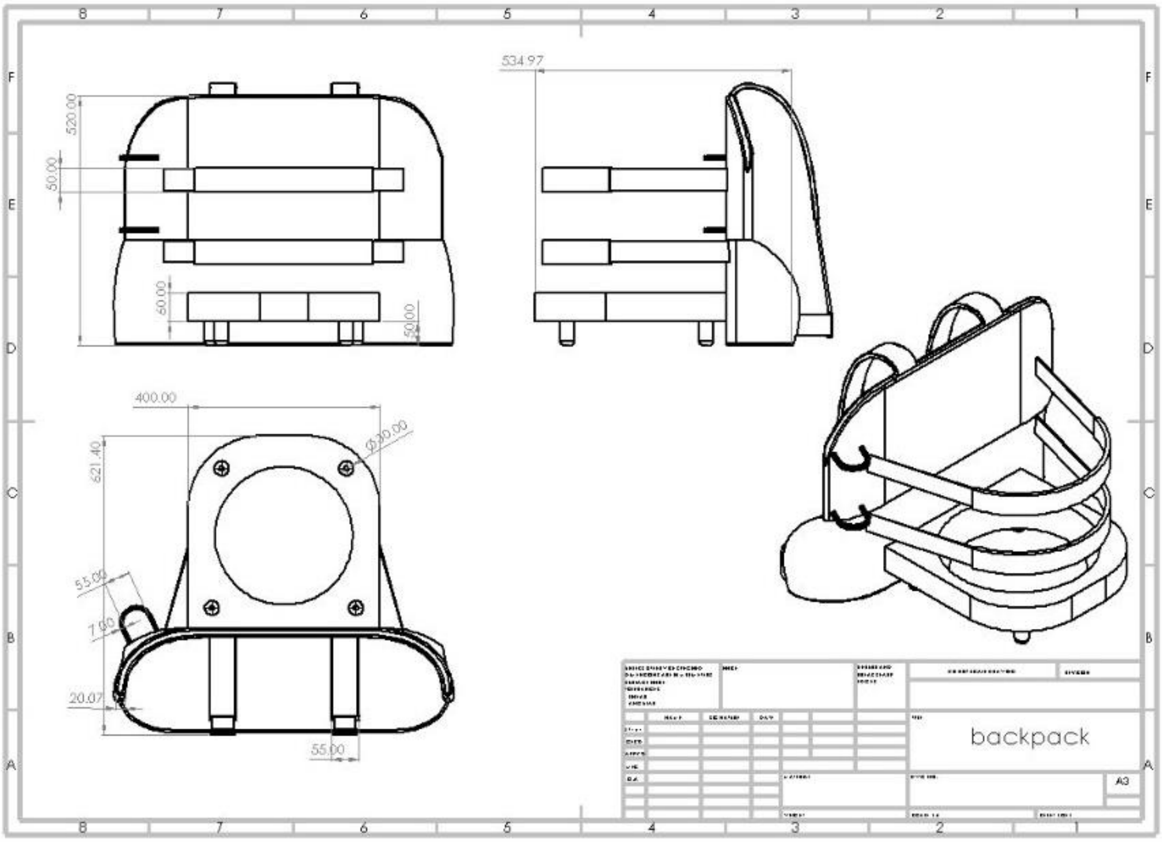
Figure 21: VaxVac

Figure 22: VaxVac in nature

A1.5 Drawing



Drawing 1: VaxVac main storage unit



Drawing 2: VaxVac carrying unit