Design and Prototyping of a Passive Cold Chain Vaccine Storage Device for Long Hold Times

David Gasperino, Ozgur Yildirim

Intellectual Ventures Laboratory

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The Vaccine Cold Chain

The Problem

Diseases like polio have been eradicated in many countries through vaccination, however, they are still prominent in large parts of the developing world.

Challenges Facing Current Vaccination Efforts

One of the greatest challenges to reaching children for vaccination is the sensitive nature of vaccines themselves, vaccines must be kept at precise temperatures until use to prevent spoiling.

The Vaccine Cold Chain

The system utilized to maintain required temperatures during storage and delivery from manufacture to the people who need it is called the "cold chain." Unfortunately, many parts of the developing world lack the infrastructure to maintain reliable cold chains and store vaccines at these precise temperatures.

Problems with the Current Vaccine Cold Chain

As a result, countless lifesaving vaccines spoil before they're administered and more importantly over 2 million children die each year because they are not immunized against preventable diseases.

The Vaccine Cold Chain Dewar

More information on the Vaccine Cold Chain Dewar can be found here:
http://seedmagazine.com/content/article/on_delivering_vaccines/

As a part of IV's Global Good program, Intellectual Ventures Lab is developing an insulated container to strengthen and extend vaccination services in developing countries.

Extending Vaccine Storage Time
The Vaccine Cold Chain Dewar is designed to keep vaccines at the appropriate temperatures for a month or more with repeat vaccine retrievals and no need for electricity.

The end result: *A device that is transportable, low cost, requires low maintenance, and can be used anywhere.*

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The Cold Chain Vaccine Storage Device

Thermal Design Conceptualization

$$q_{total} = q_{Rad} + q_{Cond,UI} + q_{Cond,Struc} + q_{Conv}$$

Radiation

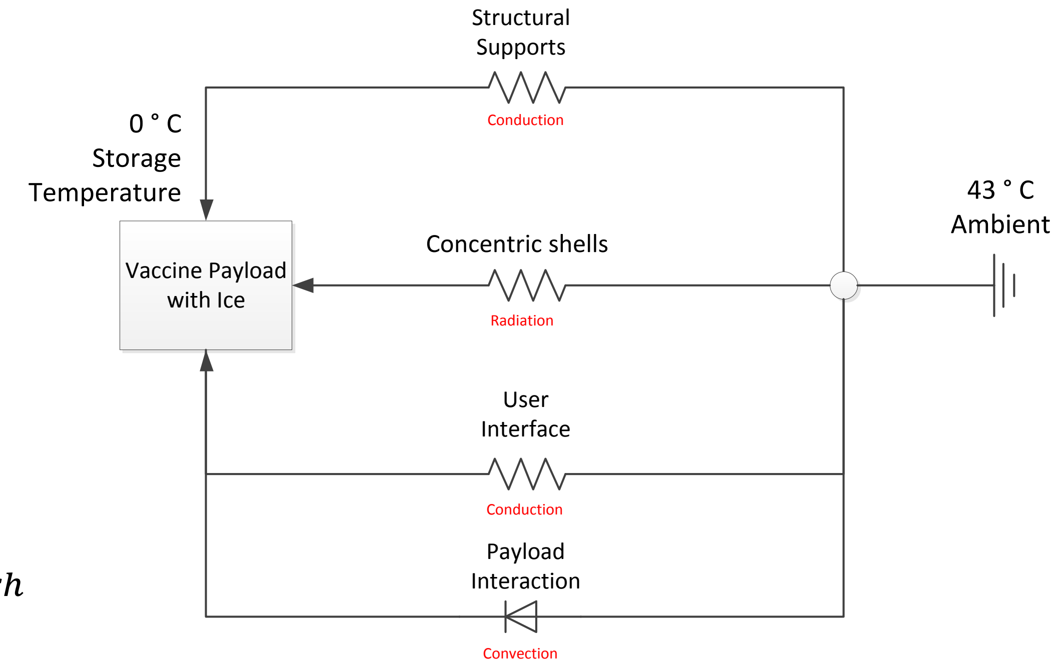
$$q_{Rad} = \varepsilon_{eff}\sigma({T_h}^4 - {T_c}^4)$$

Conduction (structural / UI)

$$q_{Cond} = \frac{kA}{L}(T_h - T_c)$$

Convection

$$q_{Conv} = m_{air}\, c_p(T_h - T_c) \times N_{exch}$$



The Cold Chain Vaccine Storage Device
Thermal Design Solution

Radiative Heat Losses

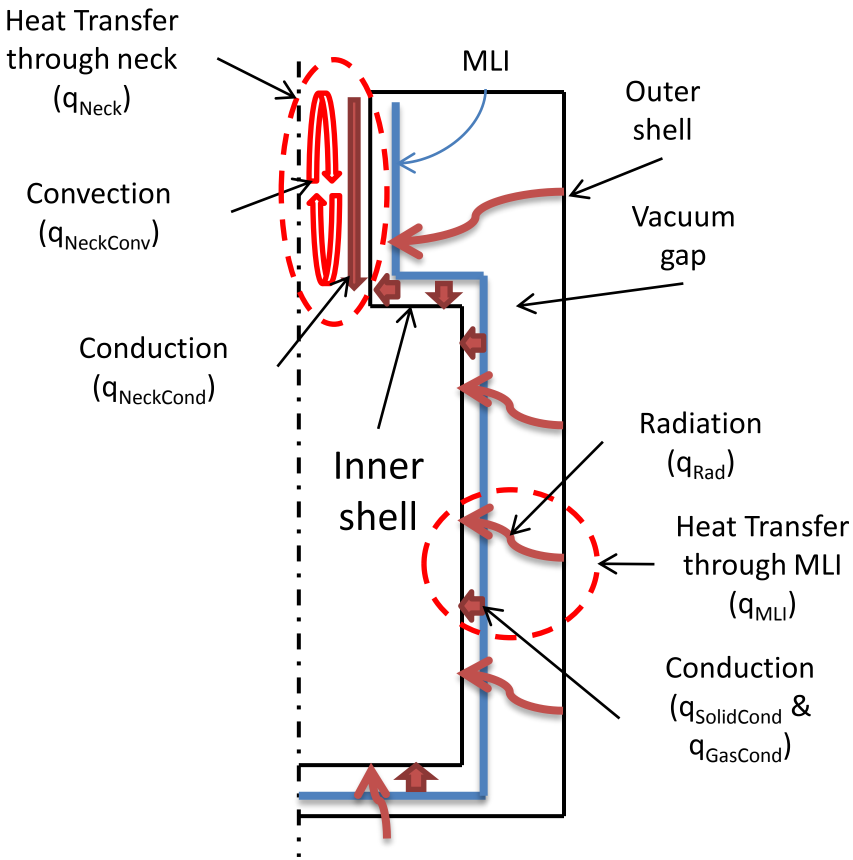
Minimized through the use of multi-layered insulation (MLI); MLI is a lightweight and highly effective barrier to radiative heat transfer.

Conductive Heat Losses

Minimized by:
1. minimizing the 'k' and 'A' of the UI, and
2. maximizing the 'L' of the UI.

Convective Heat Losses

Minimized by:
1. Pulling a vacuum between the inner and outer shells.
2. Preventing unnecessary internal air exchange.



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Multi-Layered Insulation (MLI)

Analytical Modeling of Thermal Performance

The overall heat transfer through MLI (q_{MLI}) involves three modes:

$$\boldsymbol{q_{MLI} = q_{Rad} + q_{SolidCond} + q_{GasCond}}$$

$\boldsymbol{q_{Rad}}$ = radiative heat transfer across MLI

$$q_{Rad} = \sigma\epsilon_{eff}\left(T_h^4 - T_c^4\right)$$

$\boldsymbol{q_{SolidCond}}$ = conduction across MLI due to physical contact between layers

$$q_{SolidCond} = \frac{64\alpha_s^2 k_f}{\pi^2} * \left[\left(\frac{3\pi^2(1-\mu^2)}{8E\alpha_s^2} * p\right)^{-\frac{1}{3}} + \frac{1}{\alpha_s^2}\right]^{-1} * \frac{T_h - T_c}{L}$$ [1]

$\boldsymbol{q_{GasCond}}$ = conduction through the residual gas in the interstitial space between MLI layers.

$$q_{GasCond} = \frac{C}{(n-1)\left(T_o^{0.5} + T_i^{0.5}\right)}\left(\frac{T_o - T_i}{L}\right)$$ [1]

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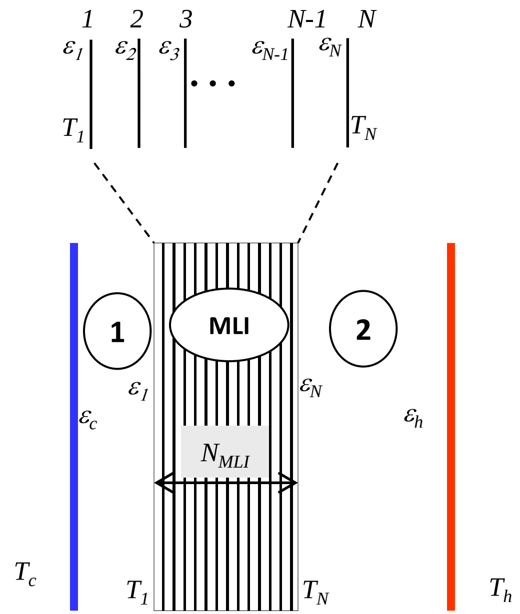
Multi-Layered Insulation (MLI)

Analytical Modeling of Thermal Performance

$$q_{MLI} = q_{Rad} + \cancel{q_{SolidCond}} + \cancel{q_{GasCond}}$$



Assuming that radiative heat transfer is the main mode of heat transfer between MLI layers, then:

$$q_{MLI} = \sigma \epsilon_{eff} \left(T_h^4 - T_c^4 \right)$$

And the analytical description for radiation exchange between large parallel plates can be extrapolated for *N* radiation shields placed between hot (*h*) and cold (*c*) surfaces to approximate ϵ_{eff} [2]:

$$\epsilon_{eff}^{-1} = \frac{1-\epsilon_h}{\epsilon_h A_h} + \left(\frac{1}{A_h F_{h,1}} \right) + \sum_{n=1}^{N} \left[\left(\frac{1-\epsilon_a}{\epsilon_a A_n} + \frac{1-\epsilon_b}{\epsilon_b A_n} \right) + \frac{1}{A_n F_{n,n+1}} \right] + \frac{1-\epsilon_c}{\epsilon_c A_c}$$

Hot surface radiative resistance	Hot surface geometrical resistance	'n' hot surface rad. resistance	'n' cold surface rad. resistance	'n' surface geo. resistance	Cold surface radiative resistance

Modeling MLI in COMSOL

Implementing Analytical BC's to Capture MLI Performance

We can make the following assumptions in order to reduce model complexity:

- $\epsilon_h \approx \epsilon_c$ for Al between 0 °C and 43 °C
- ϵ_n is evaluated at the average temperature between T_h and T_c
- $A_h \approx A_n \approx A_c$
- The view factor, *F*, between surfaces is 1

The effective emissivity, ϵ_{eff} **, can be simplified to (assuming area, A, is pulled out of the parameter* ϵ_{eff}):

$$\epsilon_{eff} * = \left(\frac{2}{\epsilon_{ave}} - 1 + \sum_{n=1}^{N} [\frac{2}{\epsilon_n} - 1] \right)^{-1}$$

The new effective emissivity, ϵ_{eff} **,* can be modeled in COMSOL as an analytical function, with N, ϵ_{ave}*, and* ϵ_n *set as parameters. A user-defined surface emissivity can be defined for the hot and cold wall boundaries after enabling the 'Surface-to-Surface Radiation' option in the 'Heat Transfer in Solids' model.*

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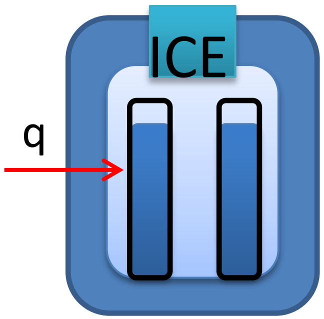
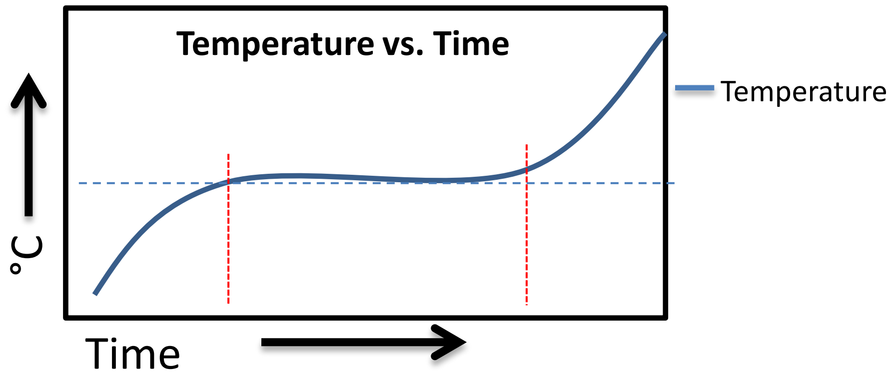
MLI Model Validation

Comparing Model Results with Experimental Measurements of Dewar Performance

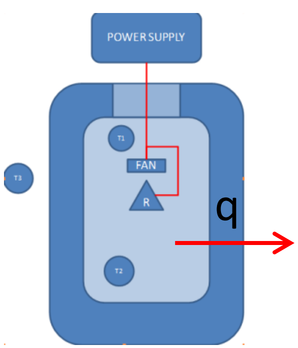
Method 1: Ice hold time

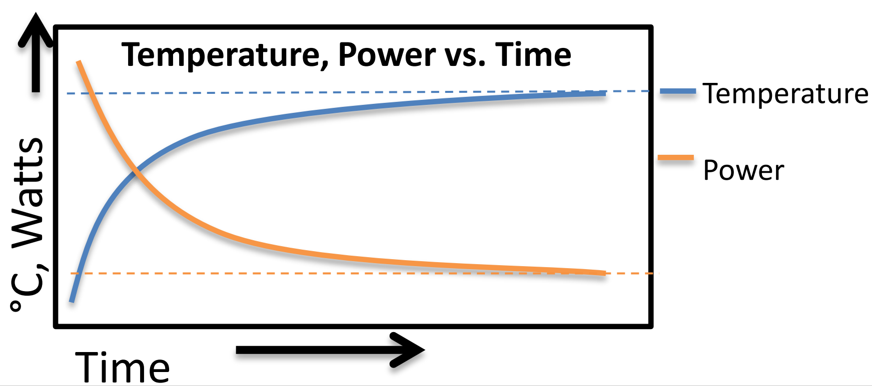




- Ice can be modeled as steady state heat sink
- Data for model comparison must come from time when system has reached steady heat transfer.

Method 2: Reverse equilibrium heat transfer

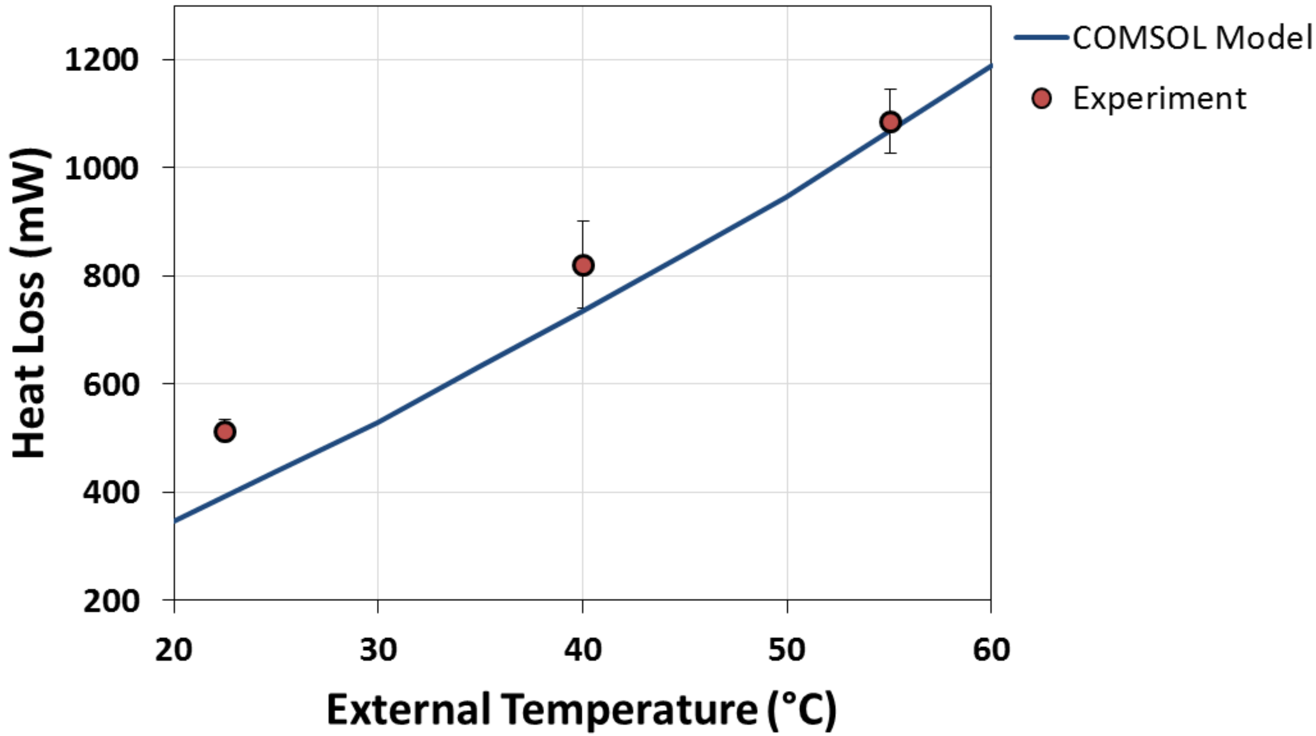


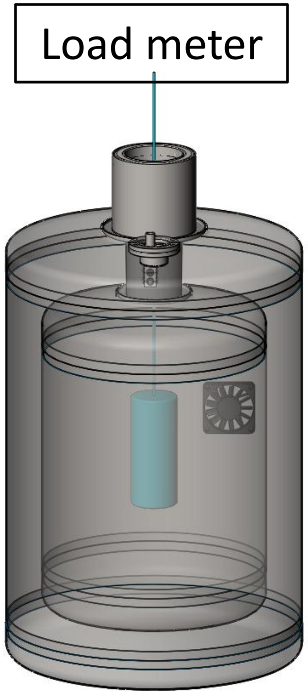


- Heat source can be modeled as steady state heat source
- Does not require ice melting phenomena to be measured
- Efficient method for validating MLI over a range of temperatures

MLI Model Validation

Comparing Model Results with Experiments



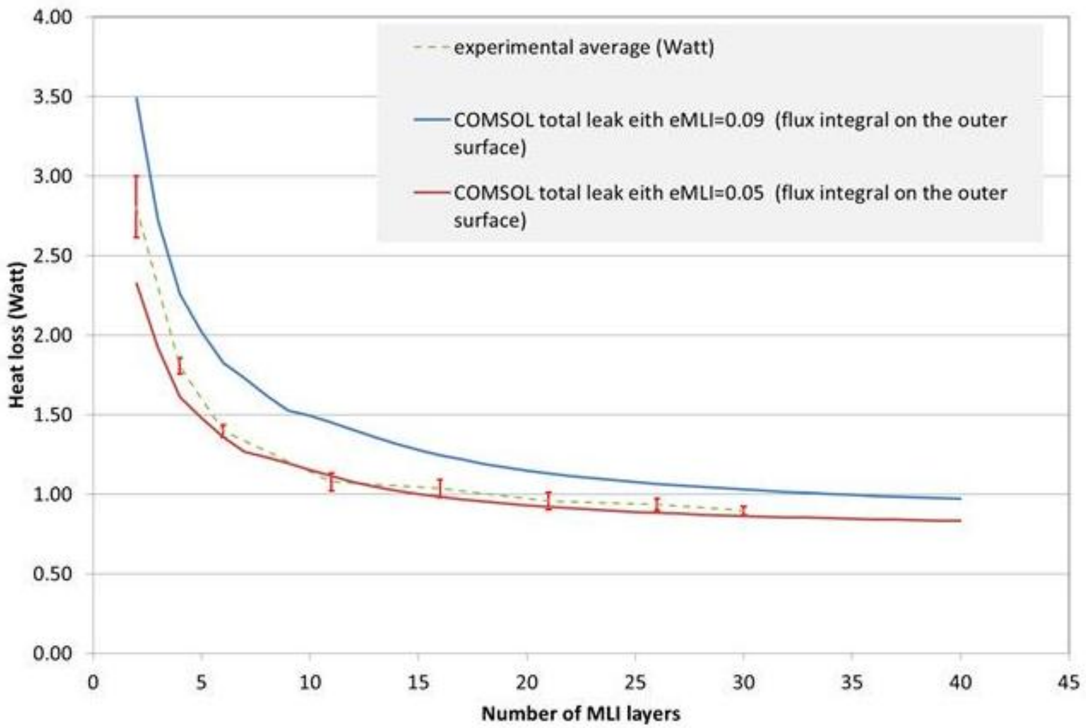


Hanging ice with fan

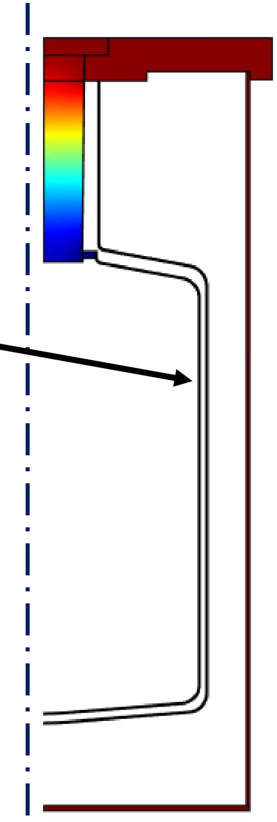
Initial model predictions assuming only radiative heat transfer through MLI gave a good idea of expected thermal performance for early prototype Dewars.

MLI Model Validation

Comparing Model Results with Experiments



In the simplest implementation, a surface-to-ambient BC is specified at this surface, with the emissivity of the surface defined as ϵ_{eff} *



Instead of adding a complex conduction fitting equation to the COMSOL model, experimental data could be used to tune ϵ_n to compensate for lower effective emissivities between the MLI layers. ***The resulting model fit experimental data well over a range of MLI layers.***

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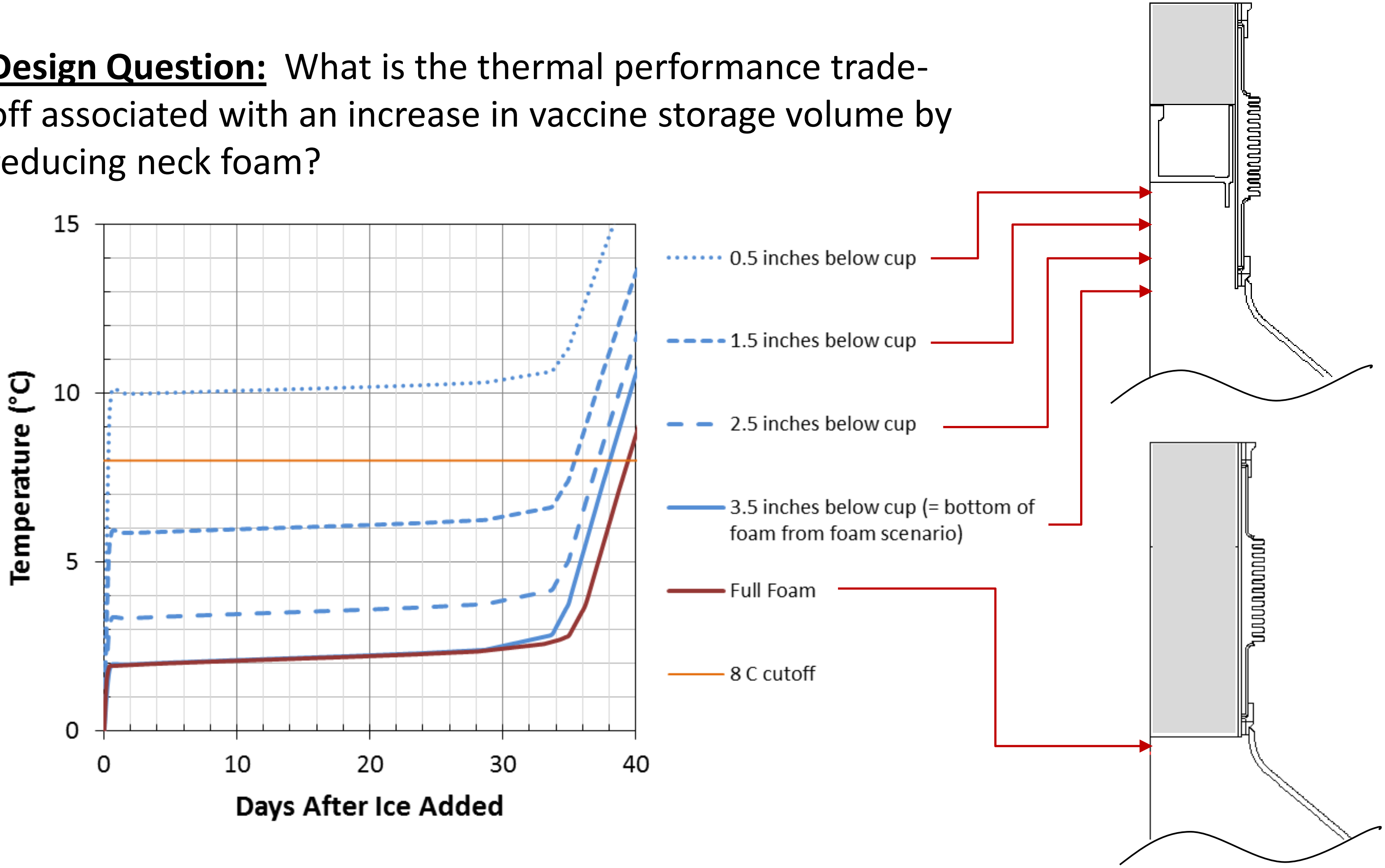
MLI Model Application

Design Tradeoff Analyses using Validated COMSOL Model

Design Question: What is the thermal performance trade-off associated with an increase in vaccine storage volume by reducing neck foam?



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Summary

- A simplified analytical approach to modeling MLI can be implemented as an effective emissivity using the Surface-to-Surface Radiation model.
- The emissivity of the MLI layers in the simplified MLI model, ϵ_n, can be modified to account for conduction across the MLI if adequate experimental data is available and a high level of model accuracy is required.
- The validated MLI model can be used to efficiently screen proposals for design changes against acceptable thermal tradeoffs.

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References

[1] B. Moshfegh, "A New Thermal Insulation System for Vaccine Distribution," *Journal of Building Physics*, vol. 15, no. 3, pp. 226-247, Jan. 1992.

[2] Incropera, F.P., Dewitt, D.P., Bergman, T.L., Lavine, A.S., Introduction to Heat Transfer, 5th ed.; John Wiley & Sons: New Jersey, 2007.

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