Design and Fabrication of a Joule Heated Fiber-Reinforced Carbon Aerogel for Insulation

Team Carbon Aerogel

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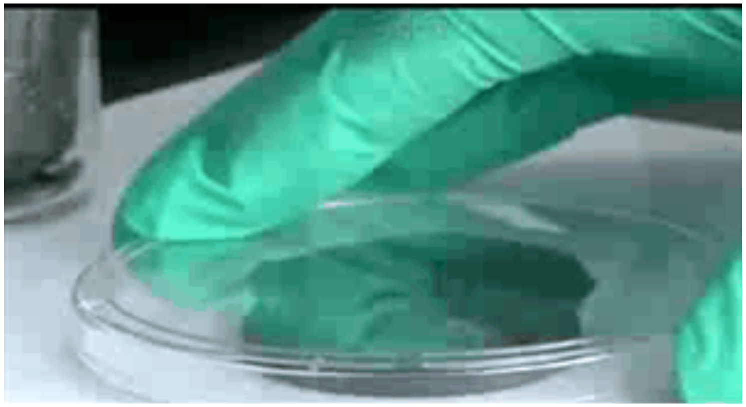
Motivation & Background

- Cold weather clothing (e.g. ECWS)
- Reduce layering/add active layer
- Novel application in lightweight active insulation

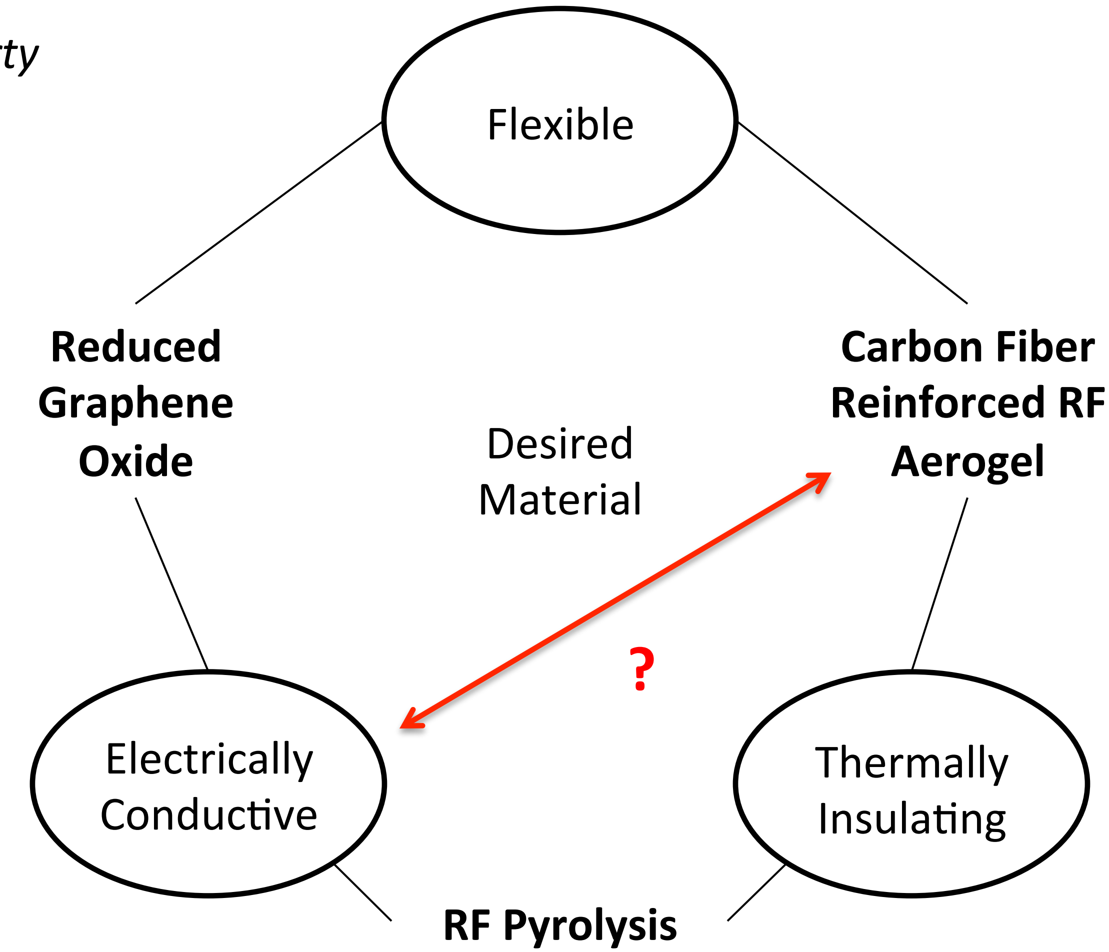


World's lightest material a possible fix for heavy problems [Video file]. (2013, May 15) Retrieved from https://youtu.be/3bIXUBXj070

- Aerogels well known for low thermal conductivities and density
- Silica aerogels characteristically brittle
- Carbon Aerogels can be processed flexibly and conductively
  - Plethora of processing methodologies exist with varying final properties
  - May be possible to joule heat an **aerogel fabric to improve cold weather performance**

Target Properties

...What process/property relationships does the literature describe?



Research Questions

(i) What is the relationship between carbon fiber content and electrical conductivity?

(ii) Can a carbon fiber reinforced carbon aerogel be joule heated to improve cold weather performance?

(iii) How would such an aerogel be fabricated if possible?

Microstructure

Electrical Properties

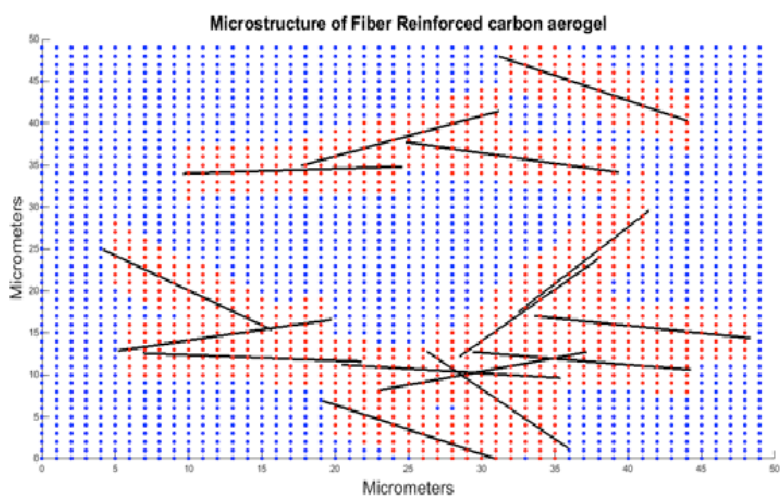
Thermal Performance

Predict Process/Property Relationship

Modelling Microstructure

Assumptions

- 2-D Microstructure
  - Yields a sheet resistance
- Fiber geometry fixed
- Pore distribution is uniform throughout aerogel



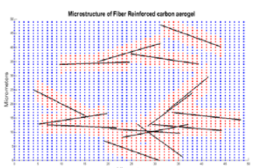
Approach

1. Define Fibers
   a. Generate a random starting point
   b. Generate endpoint as function of orientation
      i. Generate a random angle
      ii. Determine final x,y, based on fixed fiber length
2. Fill a mesh of aerogel points around lines
3. Define points and line
   - Blue is Carbon Aerogel
   - Red is Carbon Fiber

Modelling Electronic Properties

Assumptions

- Discrete line scans
  - Counteract 2-D continuity issue
- No tunneling through pores
- Tunneling between fibers can be modelled as a contact resistance



Equation 2 $$R_{sheet} = \left(\sum_{i=1}^{\frac{width}{diameter}} \frac{1}{R_{column}(i)} \right)^{-1}$$

Equation 1a $$R_{contact} = \frac{h}{2e^2} * \frac{1}{MT}$$

Equation 1b $$R_{Column} = (\#blue) * (R_{Aerogel}) + (\#red) * (R_{fiber}) + (\#blue - red) * R_{contact} + (\#red - \#blue) * R_{contact}$$

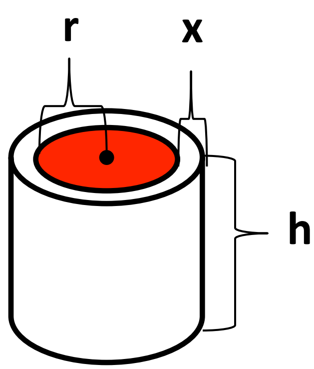
Approach

Equivalent Circuit Model

1. Consider each vertical line as a parallel resistor
2. Find resistance in each line scan (**Equation 1a and 1b)**
3. Sum resistances across parallel circuit **(Equation 2)**
4. Spread of resistivity -vs- fiber content

Modelling Thermal Performance

Assumptions



- Body Geometry
  - Height 'h' = 1.83m
  - Radius 'r' = 13cm
  - Mass 'm' = 90.72kg
  - Insulating Thickness 'x'
- Only consider conduction
  - Thermal Conductivity 'k' = 0.072 W/m-K
- Assume any joule heat goes into body
- All fluxes are constant across surface
- Simulation performed at room temperature

Approach

1. Account for heat in body currently

$$Q_0 = m_{body} c_{body} T_{body}$$

2. Account For Fluxes
   a. Out

$$J_{out} = ka\frac{T_{cold} - T_{Body}}{dx}$$

   b. In

2400kcal/day→116W

      i. Homeostasis Control

   c. 'Joule flux'

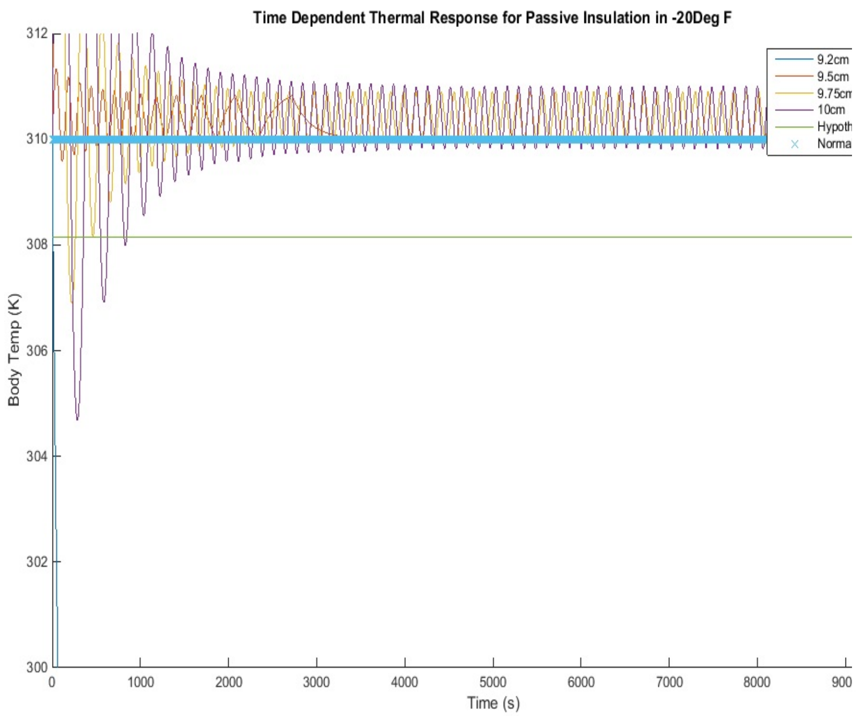
$$J_{Joule} = IR$$

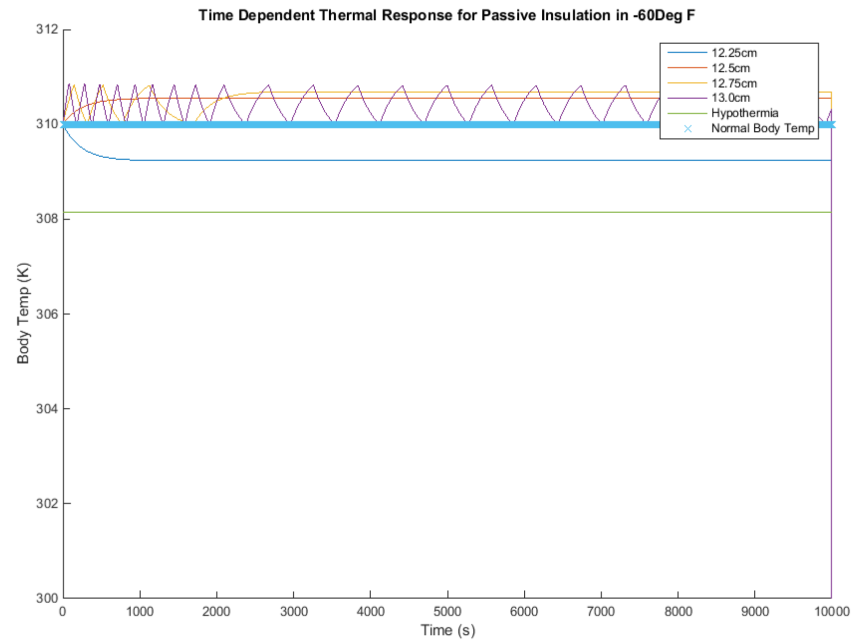
3. Iterate Through 0:dt:t_f
   a. Sum Fluxes

$$Q_{i+1} = Q_i + \left[\sum J_i\right] dt$$

   b. Check T_{body}

Modelling Results

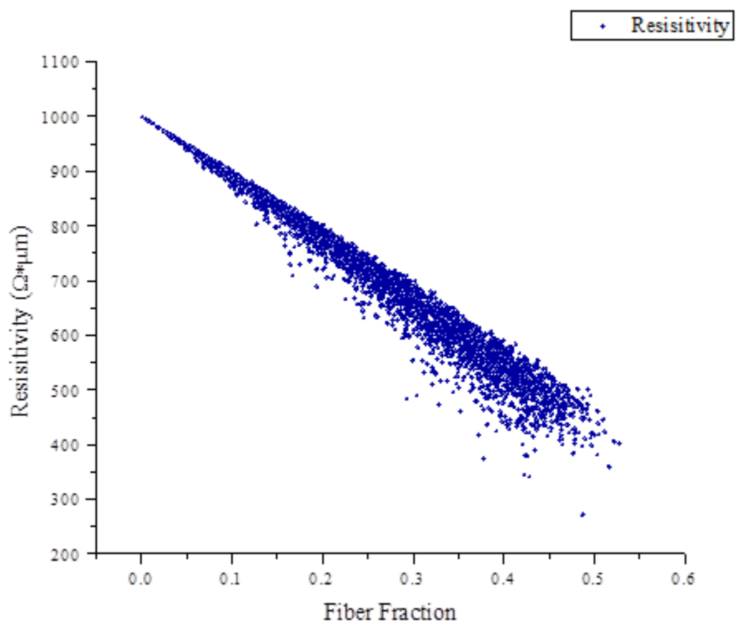




Fahrenheit

Critical insulating thickness found to be approximately 12.5cm at -60 degrees Fahrenheit

Modeling Results



Resistivity as a function of carbon fiber volume fraction.

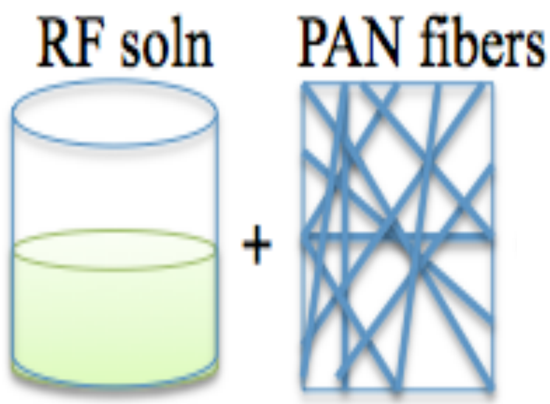
Table 3. Joule heating inadequacy (assumes cylindrical shell of length l=1.83m.

Resistivity (Ω-m)	Thickness (m)	Resistance (ohms)	Current Applied (A)	Power Generated (W)
6.40E-04	0.05	0.00373	0.1	0.000373
6.40E-04	0.05	0.00373	0.5	0.001865
6.40E-04	0.05	0.00373	1	0.003729
6.40E-04	0.05	0.00373	10	0.037299
6.40E-04	0.05	0.00373	100	0.372994

Table 4. Power generation could be increased if current is applied across thin strips instead of bulk fabric.

Resistivity (Ω-m)	Cross Sectional Area (m^2)	Resistance (ohms)	Current Applied (A)	Power Generated Per Strip (W)
6.40E-04	0.0001	1.17E+01	0.1	1.17E+00
6.40E-04	0.0001	1.17E+01	0.5	5.86E+00
6.40E-04	0.0001	1.17E+01	1	1.17E+01
6.40E-04	0.0001	1.17E+01	10	1.17E+02
6.40E-04	0.0001	1.17E+01	100	1.17E+03

Idealized Synthesis



Current Processing Restraints

- -Supercritical drier
- -Vacuum for impregnation of PAN fibers
- -Furnace for carbonization

Processing Methodologies

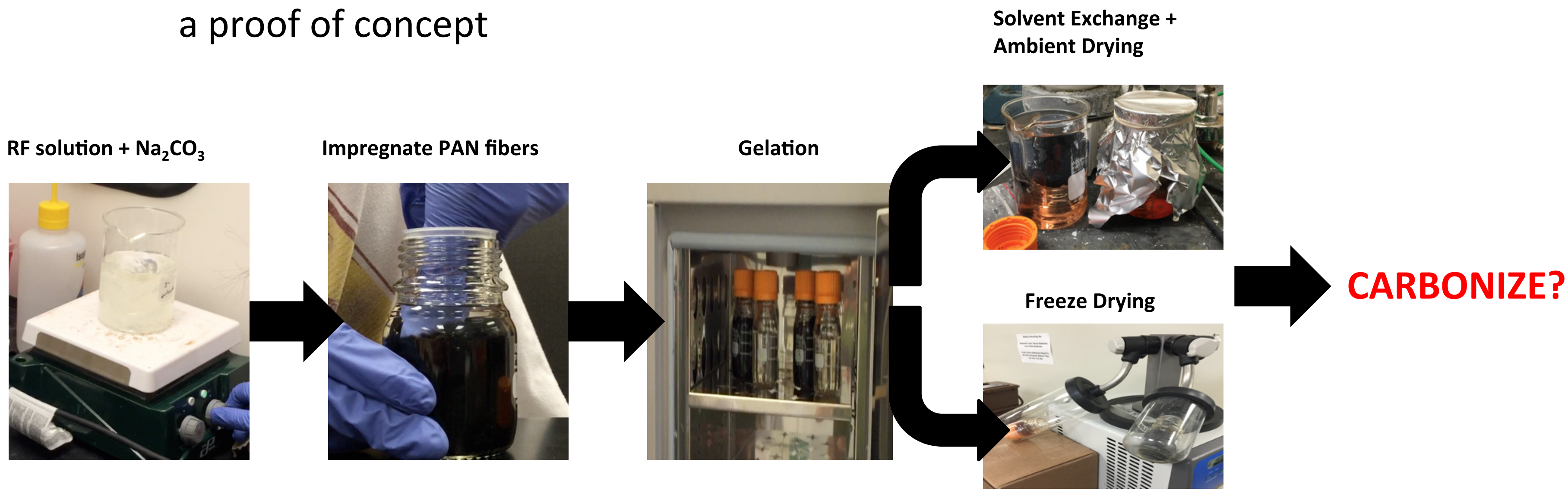
Ambient
Drying

Freeze
Drying

Supercritical
Drying

Performed Synthesis

- Mix DI water, resorcinol, formaldehyde, and sodium carbonate
  - W/R = 90, R/C = 481, F/R = 2.008
- Impregnate Pyron® Fibers *for composite creation*
- Heat at 50 C for 1 day, 95 C for 2 days *for gelation to occur*
- Ambient drying and freeze drying of Carbon Aerogel
  - Freeze drying in order to do characterization on time and ambient drying as a proof of concept



Future Work

Electrical Modeling

- Consider a 3-D microstructure
- Consider 2-D and 3-D electron mobility
- Consider temperature effects on electron mobility

Thermal Modeling

- Consider fiber content effect on ‘k’
- Consider radiation and convective losses
- Consider temperature effects on thermal properties

Aerogel Synthesis

- Supercritically dry samples in liquid CO_2
- Carbonize at 1000C in N_2 environment
- Consider variety of geometries and fiber contents

Characterization

- Confirm thermal conductivity via Differential Scanning Calorimetry
- Confirm resistivity via 4-pt probe measurements
- Perform fatigue tests to quantify flexibility

Conclusions

- Created a theoretical model of electrical resistivity as a function of carbon fiber content
- Modeled thermal performance via conductive heat losses to quantify performance
- Joule heating effects found insubstantial in current geometry
  - May still find application in different geometries
- Designed process for synthesis of idealized aerogel
  - Unable to perform synthesis due to inaccessible processing tools
  - Characterization not currently possible

Questions?

Aux - Tunneling between aerogel and fibers

$$I = \frac{2e}{h}\int_0^{\infty} \mathcal{T}(E)M(E)\left[\frac{1}{e^{\frac{E-\mu-eV}{k_B T}}+1} - \frac{1}{e^{\frac{E-\mu}{k_B T}}+1}\right]dE$$

$$I = \frac{2e}{h}\left\{\int_{\mu}^{\mu+eV} \mathcal{T}(E)M(E)dE + \frac{\pi^2}{6}(k_B T)^2 \times \frac{d[\mathcal{T}(E)M(E)]}{dE}\bigg|_{\mu}^{\mu+eV} + O\left(\frac{k_B T}{\mu}\right)^4\right\},$$

$$R_{\text{contact}} = \frac{V}{I} = \frac{h}{2e^2}\cdot\frac{1}{M\left[\mathcal{T} + \frac{\pi^2}{6}(k_B T)^2 \frac{d^2\mathcal{T}}{dE^2}\Big|_{\mu}\right]}$$

$$\mathcal{T} = \begin{cases} \exp\left(-\frac{d_{\text{vdW}}}{d_{\text{tunnel}}}\right) & 0 \le d \le D + d_{\text{vdW}} \\ \exp\left(-\frac{d-D}{d_{\text{tunnel}}}\right) & D + d_{\text{vdW}} < d \le D + d_{\text{cutoff}} \end{cases}$$

$$d_{\text{tunnel}} = \hbar/\sqrt{8m_e \Delta E}.$$

$$R_{\text{contact}} = \frac{V}{I} = \frac{h}{2e^2}\cdot\frac{1}{M\mathcal{T}\left[1 + \frac{\pi^2}{6}\left(\frac{k_B T}{\Delta E}\right)^2 \ln\mathcal{T}(\ln\mathcal{T}+1)\right]}$$

$$R_{\text{contact}} = \frac{h}{2e^2}\cdot\frac{1}{M\mathcal{T}}$$

Aux - Tunneling through pores

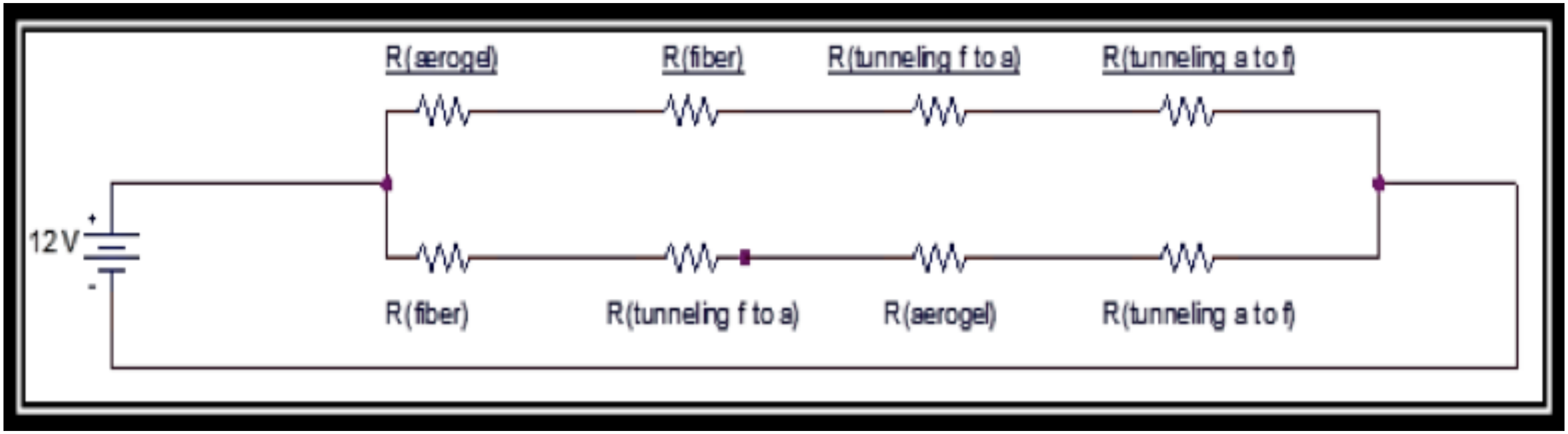
$E > V_0$

$$T = |t|^2 = \frac{1}{1 + \frac{V_0^2 \sin^2(k_1 a)}{4E(E - V_0)}}$$

$E = V_0$

$$T = \frac{1}{1 + ma^2 V_0 / 2\hbar^2}$$

Aux- Equivalent Circuit Diagram



Equivalent circuit diagram for the CFCA composite with a width of two columns/lines. R(tunneling f to a) is the tunneling resistance from fiber to aerogel and R(tunneling a to f) is the tunneling resistance from aerogel to fiber.