Thermal Analysis and Modeling

- Cooling humans
- Fundamentals of heat transfer
- Radiative equilibrium
- Surface properties
- Non-ideal effects
- Conduction
- Human thermal modeling
- Thermal system components
Cooling and Energy Use in Lunar Run

15 Minute Cooling Limit for Shuttle EVA Suits

Graph showing the relationship between speed (mph) and energy use.

- $O_2$ Transport (ml/kg/hr km)
- Heat Production (BTU/hr^2)

- Blue squares: Transport Cost
- Red squares: Heat Production

Speed (mph) axis: 0 to 6
Speed (m/s) axis: 0.0 to 3.0
Heat Production axis: 0 to 3500
$O_2$ Transport axis: 0 to 400
So What Is 2000 BTU?

- 2000 BTU/hr = 504 kcal/hr (or “calories” of food)
- Would heat 8 kg of water from body temperature (37°C) to boiling
- Water heat of vaporization = 2257 kJ/kg = 535 kcal/kg
- Need to convert 0.94 kg of water to vapor
- At 70°F, air can hold 1.15 lbs of water per KCFM
- Suit flow rate of 6 CFM = 3 gms/minute = 0.19 kg/hr = 100 kcal/hr = 397 BTU/hr
Sublimation to Dump Heat

• Flow water over porous plate exposed on other side to vacuum
  – Water passing through pores evaporates in vacuum - cools at rate of 535 kcal/kg
  – Plate reaches 0°C and water in pores freezes
  – Water at vacuum surface sublimates (solid—>gas)
    • Heat of melting 80 kcal/kg
    • Heat of vaporization 535 kcal/kg
    • Total heat of sublimation 615 kcal/kg

• Cooling 2000 BTU/hr (504 kcal/hr) requires 0.82 kg of water (ideal case)
Apollo PLSS Sublimator
Figure 45. - Sectional view of the sublimator.
Past PLSS Thermal Capacities

- **Apollo**
  - 8 hrs @ 930 BTU/hr
  - 6 hrs @ 1200 BTU/hr
  - 5 hrs @ 1600 BTU/hr

- **Shuttle/ISS EMU**
  - 7 hrs @ 1000 BTU/hr (PLSS contains 3.9 kg of water - previous calculation predicts 2.87 kg)

- **Advanced EMU (development)**
  - 8 hrs @ 1200 BTU/hr
Issues with Sublimators

• Have to be “charged” - i.e., run water through long enough to freeze porous plate
• Susceptible to contamination damage (e.g., plugging pores in plate)
• Issues with liquid / gas separation (cooling both LCVG water and suit atmosphere)
• Only works in conditions below triple point of water
Phase Curves for CO\textsubscript{2} and H\textsubscript{2}O

- CO\textsubscript{2} triple point: 216.55 K (-56.6 °C), 518 kPa
- CO\textsubscript{2} critical point: 304.25 K (31.1 °C), 7.39 MPa
- CO\textsubscript{2} sublimation point at 1 atm: 194.65 K (-78.5 °C), 101.325 kPa
- Water freezing point at 1 atm: 273.15 K (0 °C), 101.325 kPa
- Water boiling point at 1 atm: 373.15 K (100 °C), 101.325 kPa
- Water critical point: 647 K (374 °C), 22.064 MPa
- Mars

Gaits and Locomotion
Suit Membrane Water Evaporator

Ref: Bue et.al., “Long-Duration Testing of a Spacesuit Water Membrane Evaporator Prototype” 42nd ICES, AIAA 2012-3459
SWME Fundamentals

- 14,900 hollow fibers carrying water for cooling
- Hydrophobic fiber material rejects water, but allows water vapor to pass
- Chamber pressure is controlled with a back-pressure regulator
- Rate of evaporation (and rate of cooling) controlled by internal pressure in chamber
- Evaporated vapor purged through regulator to ambient
- Evaporation provides 87% of sublimation cooling
Classical Methods of Heat Transfer

- **Convection**
  - Heat transferred to cooler surrounding gas, which creates currents to remove hot gas and supply new cool gas
  - Don’t (in general) have surrounding gas or gravity for convective currents

- **Conduction**
  - Direct heat transfer between touching components
  - Primary heat flow mechanism internal to vehicle

- **Radiation**
  - Heat transferred by infrared radiation
  - Only mechanism for dumping heat external to vehicle
Ideal Radiative Heat Transfer

Planck’s equation gives energy emitted in a specific frequency by a black body as a function of temperature

\[ e_{\lambda b} = \frac{2\pi hC_0^2}{\lambda^5 \left[ \exp \left( \frac{-hC_0}{\lambda kT} \right) - 1 \right]} \]

(Don’t worry, we won’t actually use this equation for anything…)
The Solar Spectrum

Ideal Radiative Heat Transfer

Planck’s equation gives energy emitted in a specific frequency by a black body as a function of temperature

\[ e_{\lambda b} = \frac{2\pi hC_0^2}{\lambda^5 \left[ \exp \left( \frac{-hC_0}{\lambda kT} \right) - 1 \right]} \]

- Stefan-Boltzmann equation integrates Planck’s equation over entire spectrum

\[ P_{rad} = \sigma T^4 \]

\[ \sigma = 5.67 \times 10^{-8} \frac{W}{m^2 \degree K^4} \] ("Stefan-Boltzmann Constant")
Thermodynamic Equilibrium

• First Law of Thermodynamics

\[ Q - W = \frac{dU}{dt} \]

heat in -heat out = work done internally

• Heat in = incident energy absorbed

• Heat out = radiated energy

• Work done internally = internal power used
  (negative work in this sense - adds to total heat in the system)
Radiative Equilibrium Temperature

- Assume a spherical black body of radius $r$
- Heat in due to intercepted solar flux
  \[ Q_{\text{in}} = I_s \pi r^2 \]
- Heat out due to radiation (from total surface area)
  \[ Q_{\text{out}} = 4\pi r^2 \sigma T^4 \]
- For equilibrium, set equal
  \[ I_s \pi r^2 = 4\pi r^2 \sigma T^4 \Rightarrow I_s = 4\sigma T^4 \]
- 1 AU: $I_s = 1394$ W/m$^2$; $T_{eq} = 280^\circ$K
  \[ T_{eq} = \left( \frac{I_s}{4\sigma} \right)^{\frac{1}{4}} \]
Effect of Distance on Equilibrium

Black Body Equilibrium Temperature (°K)

Distance from Sun (AU)

- Mercury
- Venus
- Earth
- Mars
- Asteroids
- Jupiter
- Saturn
- Uranus
- Neptune
- Pluto
Shape and Radiative Equilibrium

- A shape absorbs energy only via illuminated faces
- A shape radiates energy via all surface area
- Basic assumption made is that black bodies are intrinsically isothermal (perfect and instantaneous conduction of heat internally to all faces)
Effect of Shape on Black Body Temps

![Graph showing the effect of shape on black body temperatures.](image-url)
Incident Radiation on Non-Ideal Bodies

Kirchhoff’s Law for total incident energy flux on solid bodies:

\[ Q_{\text{Incident}} = Q_{\text{absorbed}} + Q_{\text{reflected}} + Q_{\text{transmitted}} \]

\[ \frac{Q_{\text{absorbed}}}{Q_{\text{Incident}}} + \frac{Q_{\text{reflected}}}{Q_{\text{Incident}}} + \frac{Q_{\text{transmitted}}}{Q_{\text{Incident}}} = 1 \]

\[ \alpha \equiv \frac{Q_{\text{absorbed}}}{Q_{\text{Incident}}}; \quad \rho \equiv \frac{Q_{\text{reflected}}}{Q_{\text{Incident}}}; \quad \tau \equiv \frac{Q_{\text{transmitted}}}{Q_{\text{Incident}}} \]

where

- \( \alpha \) = absorptance (or absorptivity)
- \( \rho \) = reflectance (or reflectivity)
- \( \tau \) = transmittance (or transmissivity)
Non-Ideal Radiative Equilibrium Temp

- Assume a spherical black body of radius \( r \)
- Heat in due to intercepted solar flux
  \[ Q_{in} = I_s \alpha \pi r^2 \]
- Heat out due to radiation (from total surface area)
  \[ Q_{out} = 4\pi r^2 \varepsilon \sigma T^4 \]
- For equilibrium, set equal

\[ I_s \alpha \pi r^2 = 4\pi r^2 \varepsilon \sigma T^4 \implies I_s = 4 \frac{\varepsilon}{\alpha} \sigma T^4 \]

\[ T_{eq} = \left( \frac{\alpha I_s}{\varepsilon 4\sigma} \right)^\frac{1}{4} \]
Effect of Surface Coating on Temperature

\( \varepsilon = \text{emissivity} \)

\( \alpha = \text{absorptivity} \)

- Black Ni, Cr, Cu
- Black Paint
- Aluminum Paint
- Polished Metals
- White Paint
- Optical Surface Reflector

- Teq=560°K (a/e=4)
- Teq=471°K (a/e=2)
- Teq=396°K (a/e=1)
- Teq=333°K (a/e=0.5)
- Teq=280°K (a/e=0.25)
Non-Ideal Radiative Heat Transfer

- Full form of the Stefan-Boltzmann equation
  \[ P_{rad} = \varepsilon \sigma A \left( T^4 - T_{env}^4 \right) \]
  where \( T_{env} \) = environmental temperature (\( = 4°K \) for space)

- Also take into account power used internally
  \[ I_s \alpha A_s + P_{int} = \varepsilon \sigma A_{rad} \left( T^4 - T_{env}^4 \right) \]
Example: AERCam/SPRINT

- 30 cm diameter sphere
- $\alpha=0.2; \ \varepsilon=0.8$
- $P_{\text{int}}=200W$
- $T_{\text{env}}=280^\circ\text{K}$ (cargo bay below; Earth above)

- Analysis cases:
  - Free space w/o sun
  - Free space w/sun
  - Earth orbit w/o sun
  - Earth orbit w/sun
AERCam/SPRINT Analysis (Free Space)

- $A_s=0.0707 \text{ m}^2; A_{rad}=0.2827 \text{ m}^2$
- Free space, no sun

$$P_{\text{int}} = \varepsilon\sigma A_{rad} T^4 \Rightarrow T = \left( \frac{200W}{0.8\left(5.67 \times 10^{-8} \frac{W}{m^2\circ K^4}\right)\left(0.2827 m^2\right)} \right)^{1/4} = 354 \circ K$$
AERCam/SPRINT Analysis (Free Space)

- $A_s = 0.0707 \, \text{m}^2$; $A_{rad} = 0.2827 \, \text{m}^2$
- Free space with sun

$$I_s \alpha A_s + P_{\text{int}} = \varepsilon \sigma A_{rad} T^4 \Rightarrow T = \left( \frac{I_s \alpha A_s + P_{\text{int}}}{\varepsilon \sigma A_{rad}} \right)^{1/4} = 362^\circ K$$
AERCam/SPRINT (LEO Cargo Bay)

- $T_{\text{env}} = 280^\circ \text{K}$
- LEO cargo bay, no sun

$$P_{\text{int}} = \varepsilon \sigma A_{\text{rad}} (T^4 - T_{\text{env}}^4) \Rightarrow T = \left( \frac{200W}{0.8 \left( 5.67 \times 10^{-8} \frac{W}{m^2^\circ K^4} \right) (0.2827 m^2)} + (280^\circ \text{K})^4 \right)^{\frac{1}{4}} = 384^\circ \text{K}$$

- LEO cargo bay with sun

$$I_s \alpha A_s + P_{\text{int}} = \varepsilon \sigma A_{\text{rad}} (T^4 - T_{\text{env}}^4) \Rightarrow T = \left( \frac{I_s \alpha A_s + P_{\text{int}}}{\varepsilon \sigma A_{\text{rad}}} + T_{\text{env}}^4 \right)^{\frac{1}{4}} = 391^\circ \text{K}$$
Radiative Insulation

- Thin sheet (mylar/kapton with surface coatings) used to isolate panel from solar flux
- Panel reaches equilibrium with radiation from sheet and from itself reflected from sheet
- Sheet reaches equilibrium with radiation from sun and panel, and from itself reflected off panel
Multi-Layer Insulation (MLI)

- Multiple insulation layers to cut down on radiative transfer
- Gets computationally intensive quickly
- Highly effective means of insulation
- Biggest problem is existence of conductive leak paths (physical connections to insulated components)
Emissivity Variation with MLI Layers

MLI Thermal Conductivity

\[
K_{\text{eff}} = \left[ 1.027 \times 10^{-7} \frac{T_H + T_C}{2} + 3.333 \times 10^{-16} \frac{T_H^{4.67} - T_C^{4.67}}{T_H - T_C} \right] \times 0.625
\]

\[T_H = 300 \text{ K}\]
\[T_H = 250 \text{ K}\]
\[T_H = 200 \text{ K}\]
\[T_H = 150 \text{ K}\]
\[T_H = 100 \text{ K}\]
\[T_H = 60 \text{ K}\]


- Double aluminized Mylar with Tissueglass spacers
- 110 layers/in. (0.75 to 1.25 in.)
- Pressure = 10^{-6} Torr
- \(T_H\) = Hot boundary temperature (°R)
- \(T_C\) = Cold boundary temperature (°R)
Effect of Ambient Pressure on MLI

1D Conduction

• Basic law of one-dimensional heat conduction (Fourier 1822)

\[ Q = -KA \frac{dT}{dx} \]

where

K=thermal conductivity (W/m\(^\circ\)K)
A=area
dT/dx=thermal gradient
3D Conduction

General differential equation for heat flow in a solid

\[ \nabla^2 T(r,t) + \frac{g(r,t)}{K} = \frac{\rho c}{K} \frac{\partial T(r,t)}{\partial t} \]

where

- \( g(r,t) \) = internally generated heat
- \( \rho \) = density (kg/m³)
- \( c \) = specific heat (J/kg°C)
- \( K/\rho c \) = thermal diffusivity
Simple Analytical Conduction Model

- Heat flowing from (i-1) into (i)

\[ Q_{in} = -KA \frac{T_i - T_{i-1}}{\Delta x} \]

- Heat flowing from (i) into (i+1)

\[ Q_{out} = -KA \frac{T_{i+1} - T_i}{\Delta x} \]

- Heat remaining in cell

\[ Q_{out} - Q_{in} = \frac{\rho c}{K} \frac{T_i(j + 1) - T_i(j)}{\Delta t} \]
Finite Difference Formulation

- Time-marching solution

\[ T_{i}^{n+1} = T_{i}^{n} + d(T_{i+1}^{n} - 2T_{i}^{n} + T_{i-1}^{n}) \]

where

\[ d = \frac{\alpha \Delta t}{\Delta x^2} \quad \alpha = \frac{k}{\rho C_v} = \text{thermal diffusivity} \]

- For solution stability,

\[ \Delta t < \frac{\Delta x^2}{2\alpha} \]
Human Thermal Model (Wissler)

- 15 elements per body
- 15 nodes per element
- Additional elements: e.g., skin, sweat, air circulation
- ~300 nodes in full model
Human Thermal Model (METMAN)

- 10 elements in body
- 4 nodes per element
  - Skin
  - Fat
  - Muscle
  - Core
- Blood is separate node
- 41 nodes total
Energy Balance in Each Node

\[ Q_{st} = Q_m - Q_c - Q_r - Q_e - Q_k - Q_{resp} - Q_{LCG} = mc_p \frac{\partial T}{\partial t} \]

- \( Q_{st} \) - heat rate saved into tissue
- \( Q_m \) - heat rate due to internal metabolism
- \( Q_c \) - heat rate due to surface convection
- \( Q_r \) - heat rate due to radiative losses
- \( Q_e \) - heat rate due to evaporation
- \( Q_k \) - heat rate due to conduction to other nodes
- \( Q_{resp} \) - heat rate due to respiratory cooling
- \( Q_{LCG} \) - heat rate due to liquid cooling garment
41-Node Heat Flow Equations (1)

Core layer:

\[ M_c C_p c \frac{dT_c}{dt} = \dot{m}_b \rightarrow c C_p b (T_b - T_c) + G_m \leftrightarrow c (T_m - T_c) \]

\[ + \dot{Q}_{\text{met}} - \dot{Q}_{\text{resp}} \]

Muscle layer:

\[ M_m C_p m \frac{dT_m}{dt} = \dot{m}_b \rightarrow m C_p b (T_b - T_m) + G_c \leftrightarrow m (T_c - T_m) \]

\[ + G_f \leftrightarrow m (T_f - T_m) + \dot{Q}_{\text{met}} - \dot{Q}_{\text{shiv}} - \dot{Q}_{\text{resp}} \]

41-Node Heat Flow Equations (2)

ISS Radiator Assembly
Case Study: ECLIPSE Thermal Analysis

- Developed by UMd SSL for NASA ESMD
- Minimum functional habitat element for lunar outpost
- Radiator area - upper dome and six upper cylindrical panels
ECLIPSE Heat Sources

- Solar heat load (modeling habitat as right circular cylinder)
  \[ A_{\text{illuminated}} = \ell d \sin \beta + \frac{1}{4} \pi d^2 \cos \beta \]

- Electrical power load = 4191 W

- Metabolic work load (4 crew) = 464 W
Thermal Modeling for Lunar Surface

- Assume upper dome radiates only to deep space
- Assume side panels radiate half to deep space and half to lunar surface
- Assume (conservatively) that lunar surface radiates as a black body

\[
Q_{\text{internal}} + Q_{\text{solar}} = \epsilon\sigma \left[ A_{\text{dome}} T_{\text{rad}}^4 + n_{\text{rad}} A_{\text{panel}} \left( T_{\text{rad}}^4 - \frac{1}{2} T_{\text{moon}}^4 \right) \right]
\]

\[
T_{\text{rad}} = \left[ \frac{1}{A_{\text{dome}} + n_{\text{rad}} A_{\text{panel}}} \left( \frac{Q_{\text{internal}} + Q_{\text{solar}}}{\epsilon\sigma} + \frac{1}{2} n_{\text{rad}} A_{\text{wall}} T_{\text{moon}}^4 \right) \right]^{\frac{1}{4}}
\]
# ECLIPSE Thermal Results

<table>
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<tr>
<th>Case</th>
<th>Solar Angle (deg)</th>
<th>Lunar Surface Temp (K)</th>
<th>Active Panels</th>
<th>Wall</th>
<th>Radiator Temp (K)</th>
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<td>6†</td>
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<td>290</td>
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</table>

†Radiator geometry modified to reduce total lunar surface exposure