• Lecture #19 – November 3, 2020
• Fundamentals of heat transfer
• Radiative equilibrium
• Surface properties
• Non-ideal effects
  – Internal power generation
  – Environmental temperatures
• Conduction
• Thermal system components
Mid-Term Exam

• Thursday 11/5 on Gradescope
• Calculator
• Open notes
• On lectures 1-11
• Remind me (dakin@ssl.umd.edu) if you have an accommodation
Venus Fly-By Mission (TuTh 11:00-12:15)

<table>
<thead>
<tr>
<th>Avionics, Flight Software, and Simulation</th>
<th>Mission Planning and Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benz Huynh</td>
<td>Brent Jones</td>
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<tr>
<td>Joshua Martin</td>
<td>Henry Hover</td>
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<td>Matthew Palmer</td>
<td>Juan Rodriguez</td>
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<td>Thara Konduri</td>
<td>Lauren Meyers</td>
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<td>Yash Mehta</td>
<td>Nil Patel</td>
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<td><strong>Crew Systems</strong></td>
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<td>Rachel Harvey</td>
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<td><strong>Loads, Structures, and Mechanisms</strong></td>
<td>William Kleyman</td>
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<td>Ian Down</td>
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<td>Sam Shrestha</td>
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<td>Stella Hurtt</td>
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<td>Thanushree Manjunath</td>
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Lead Instructor: Becnel
# Human Mission to Ceres (TuTh 5-6:15)

## Avionics, Flight Software, and Simulation
- Galen Bascom
- Matthew Rozek
- Sean O'Connor

## Crew Systems
- Aerik Moitra
- Gismarie Bermudez
- Khushbu Jain
- Michael Neary

## Loads, Structures, and Mechanisms
- Amelia Cherian
- Farouk Tijani
- Jack Hamrock
- Micah Calderwood

## Mission Planning and Analysis
- Anusha Dixit
- Christian Olson
- Jessica Bleich
- Rachel Cueva

## Power, Propulsion, and Thermal
- Chase McConville
- Richard Francis
- William Bernlohr

## Systems Integration
- Adam Schneider
- Jonathan Molter
- Ryan Ruschak
- Shailesh Murali

**Lead Instructor: Young**
<table>
<thead>
<tr>
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<tr>
<td>Andre Nadeau</td>
<td>Christopher Klug</td>
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<td>Giovanna Amorim</td>
<td>Hridoy Stanislaus Rozario</td>
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<td>Alexandria Spittel</td>
<td>Saatwik Bandyopadhyay</td>
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<td>Marco Navarro</td>
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<td>Stefan Fasano</td>
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<td>Elizabeth Barranco</td>
<td>Benjamin Brotsman</td>
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<td>Chinmay Sevak</td>
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<td>Kyle Callaghan</td>
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<td>Raghav Srivastava</td>
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Lead Instructors: Akin/Bowden
# Lunar Habitat (MW 3:30-4:45)

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<td>Collin Miller</td>
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<td>Lee Berny Gifwandi</td>
<td>Ethan Kramer</td>
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<td>Muhammad A. Khalid</td>
<td>Imran Khawaja</td>
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<td>Bailey Konold</td>
<td>Jaylen Nathwani</td>
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<td>Autumn Russell</td>
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<td>Ethan Stowell</td>
<td>Gilad Gensler</td>
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<td>Jessica Queen</td>
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Lead Instructors: Akin/Bowden
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

\[ e_{\lambda b} = \frac{2\pi h C_0^2}{\lambda^5 \left[ \exp \left( \frac{-h C_0}{\lambda k T} \right) - 1 \right]} \]

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

\[ P_{rad} = \sigma T^4 \quad \sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4} \] ("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
  \[ Q_{in} = I_s \pi r^2 \]
• Heat out due to radiation (from total surface area)
  \[ Q_{out} = 4\pi r^2 \sigma T^4 \]
• 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: $I_s = 1394 \text{ W/m}^2$; $T_{eq} = 280^\circ \text{K}$
  \[ T_{eq} = \left( \frac{I_s}{4\sigma} \right)^{1/4} \]
Effect of Distance on Equilibrium Temp

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. The graph plots distance from the sun (in AU) on the x-axis and black body equilibrium temperature on the y-axis. Three curves are shown: Spherical Black Body, Adiabatic Black Wall, and Double-Sided Wall. The Spherical Black Body curve is the highest, followed by the Adiabatic Black Wall, and then the Double-Sided Wall.]
Incident Radiation on Non-Ideal Bodies

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

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

where

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

- Assume a spherical 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
  \[
  I_s \alpha \pi r^2 = 4\pi r^2 \varepsilon \sigma T^4 \implies I_s = 4 \frac{\varepsilon}{\alpha} \sigma T^4
  \]
  \[
  T_{eq} = \left( \frac{\alpha I_s}{\varepsilon 4\sigma} \right)^{1/4}
  \]

(\( \varepsilon \) = “emissivity” - efficiency of surface at radiating heat)
Effect of Surface Coating on Temperature

- $\varepsilon =$ emissivity
- $\alpha =$ absorptivity

Graph showing the relationship between absorptivity and emissivity for different surface coatings:
- Black Ni, Cr, Cu
- Black Paint
- Aluminum Paint
- Polished Metals
- White Paint
- Optical Surface Reflector

Lines indicating different temperatures:
- $Teq=560^\circ K$ ($a/e=4$)
- $Teq=471^\circ K$ ($a/e=2$)
- $Teq=396^\circ K$ ($a/e=1$)
- $Teq=333^\circ K$ ($a/e=0.5$)
- $Teq=280^\circ K$ ($a/e=0.25$)
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 (\( = 4^\circ\text{K for space} \))

• 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
- $\alpha = 0.2; \epsilon = 0.8$
- $P_{\text{int}} = 200W$
- $T_{\text{env}} = 280^\circ K$ (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

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

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

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

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

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

- LEO cargo bay with sun

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

Finer Detail on Effective Emissivity

![Graph showing the relationship between effective emittance and number of aluminized mylar layers. The graph includes data points for OAO Installed, LM Installed, LM Blanket Tests, Incl Supports, Vents and Seams, and LM Blanket Tests Bare Blanket. Theoretical Curve is also shown with $\varepsilon_{MY} = 0.40$ and $\varepsilon_{AL} = 0.05$.](image)
Estimating Function for MLI

\[
\epsilon_{eff} = \left( \frac{2n}{\epsilon_{mylar}} - n - 1 + \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} \right)
\]

\[
\epsilon_{mylar} = 0.03
\]

\[n = \text{number of MLI layers} \]

\[\epsilon_1 = \text{emissivity of coating on side 1} \]

\[\epsilon_2 = \text{emissivity of coating on side 2} \]
MLI Thermal Conductivity

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

- Double aluminized Mylar with Tissueglass spacers
- 110 layers/in. (0.75 to 1.25 in.)
- Pressure = $10^{-6}$ Torr
- $T_H =$ Hot boundary temperature ($\,^\circ$R)
- $T_C =$ Cold boundary temperature ($\,^\circ$R)

Effect of Ambient Pressure on MLI

Silica Aerogel Insulation

1D Conduction

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

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

where

- \( K \) = thermal conductivity (W/m°K)
- \( A \) = area
- \( \frac{dT}{dx} \) = 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/m\(^3\))
\( c \) = specific heat (J/kg°K)
\( K/\rho c \) = 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

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

- For solution stability,

\[ \Delta t < \frac{\Delta x^2}{2\alpha} \]
Thermal Control Elements

- Passive systems
  - Coatings
  - Heat shunts
  - Multilayer insulation
  - Heat pipes

- Active systems
  - Heaters
  - Louvers
  - Pumped fluid loops
Heat Pipe Schematic

<table>
<thead>
<tr>
<th>fluid</th>
<th>melting point ($^\circ$C)</th>
<th>boiling point ($^\circ$C)</th>
<th>critical point ($^\circ$C)</th>
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<tbody>
<tr>
<td>Methane ($CH_4$)</td>
<td>$-182.5$</td>
<td>$-161.8$</td>
<td>$-82.6$</td>
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<tr>
<td>Methanol ($CH_3OH$)</td>
<td>$-97.9$</td>
<td>$64.8$</td>
<td>$240.0$</td>
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<tr>
<td>Acetone ($CH_3COCH_3$)</td>
<td>$-93.2$</td>
<td>$56.25$</td>
<td>$235.1$</td>
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<tr>
<td>Ammonia ($NH_3$)</td>
<td>$-77.7$</td>
<td>$-33.4$</td>
<td>$132.4$</td>
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<tr>
<td>Water ($H_2O$)</td>
<td>$0(.05)$</td>
<td>$100$</td>
<td>$374.2$</td>
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Thermal Louvers

Pumped Fluid Loops
Shuttle Thermal Control Components

Typical Radiator Panel
Physical Characteristics

Space Shuttle Active
Thermal Control Subsystem

Outlet Manifold

105 ft.

Facesheet (.08")

68 Parallel Flow Tubes
0.131 In. I.D.
Silver/Teflon Coating Both Sides
μ = .17, ε = .76

NH3 Boiler

GSE H-X
Hydraulics
Flash
Evaporator

Fuel Cell
Flow Proportioning Module
Freon 21 Pump Package
Interchanger

From Radiators
To Radiators

Midbody Coldplates
Radiator Flow Control Assembly

(One Loop Shown)
Shuttle Thermal Control System Schematic
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)

\[ A_{illuminated} = \ell d \sin \beta + \frac{1}{4} \pi d^2 \cos \beta \]

\[ Q_{solar} = A_{illuminated} \alpha I_s \]

- 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>
<thead>
<tr>
<th>Case</th>
<th>Solar (deg)</th>
<th>Angle</th>
<th>Lunar Temp (K)</th>
<th>Surface Temp (K)</th>
<th>Active Panels</th>
<th>Wall</th>
<th>Radiator Temp (K)</th>
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<tbody>
<tr>
<td>Polar Outpost Day</td>
<td>88</td>
<td></td>
<td>180</td>
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<td>283</td>
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<td>Local Midnight</td>
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<td>120</td>
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<td>380</td>
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<td>6†</td>
<td></td>
<td>290</td>
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†Radiator geometry modified to reduce total lunar surface exposure