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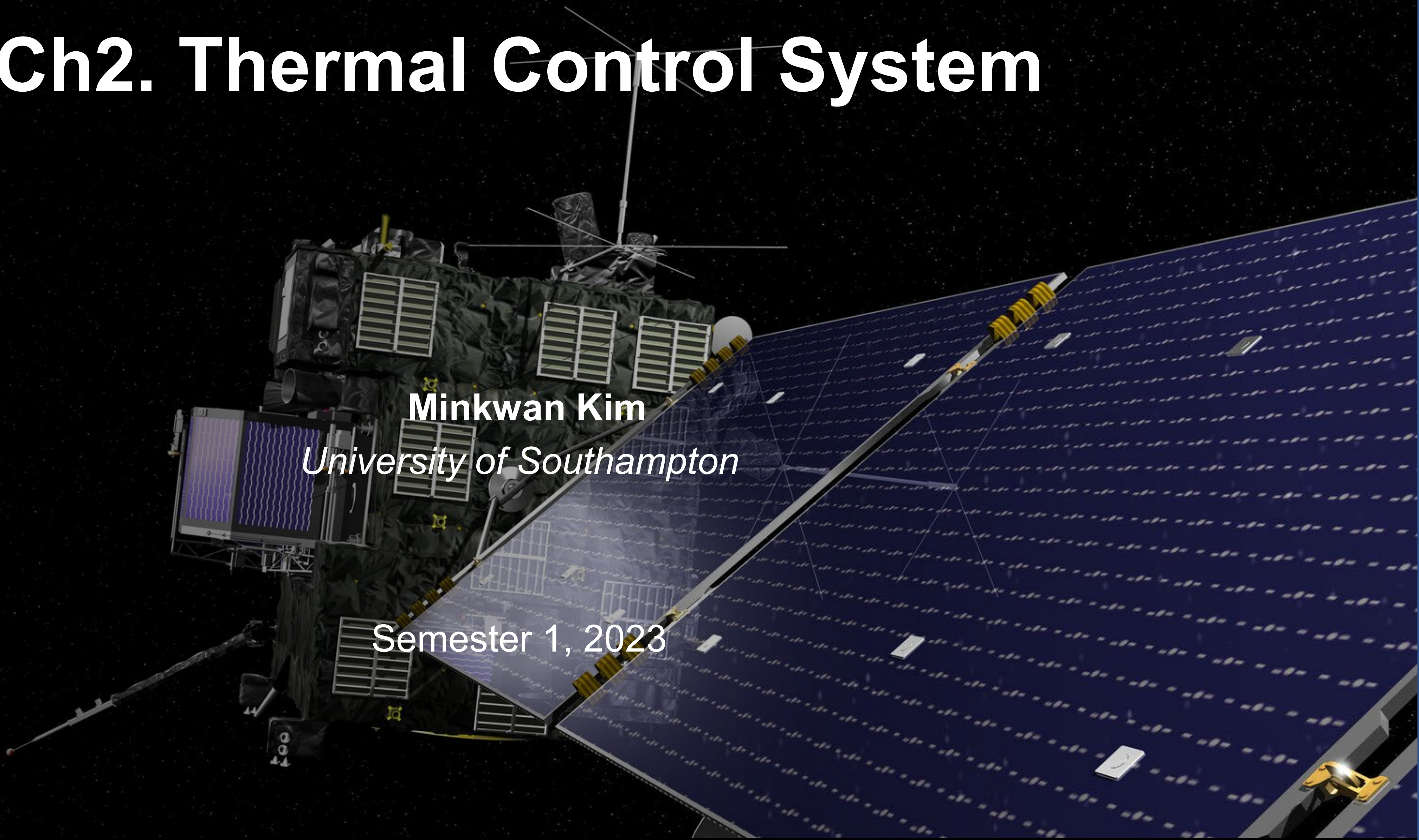
Ch2. Thermal Control System



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1. **Introduction**
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NOTE (Important)

- There will be an online quiz for Chapter 2 via Blackboard
- Your quiz **MUST** be submitted by the due (8/Jan/2024 9:00)
- No extension will be allowed

2.1 Introductions

generally 95~98% is passive

Introduction

- Maintain **all of the elements** of a spacecraft system within their temperature limits for **all mission phases.**
  - Passive system & Active system allways used in crewed cases, or for precise instrument target temp.
  - Must account for heat inputs from many different sources

  <u>Examples of heat sources</u>
  - Sun
  - Earth
  - Heat dissipation from electrical and electronic components onboard spacecraft

<u>NOTE:</u>

Heat inputs are highly variable with time (eg. Magnitude of direct solar heating: 1371 W/m^2 -> Zero) eclipse

- Variation of heat input + complex geometry of spacecraft ➔ thermal analysis to be extremely complicated

- High computational resource is required, but Thermal control system account for only about **2 ~3 %** of the total spacecraft cost and about the same percentage of the weight

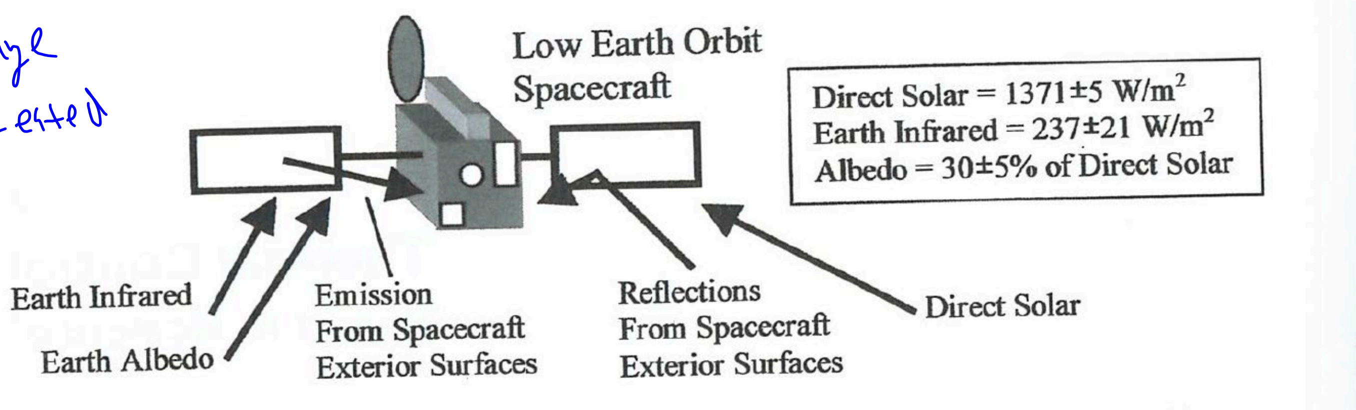
Requirements for a spacecraft thermal control system

- **Top-level system requirements** defines:
  - Temperature margins → component temp range
  - Overall testing requirements → how it's tested
  - Environmental definitions →

heat cooling cycles can cause wear

- **Derived requirements:**
  - Subsystem weight allocation
  - Cost goal

- Temperature limit defined by:
  - Various subsystem groups for their components based on supplier data



Thermal radiation environment

Component	Typical temperature range, ℃	Component	Typical temperature range, ℃
Batteries, NiCd	5 to 20	Mylar	-73 to 149
Batteries, NiH	-10 to 20	Nylon	-73 to 150
Electronics	0 to 40	Solar arrays	-100 to 100
Hydrazine	7 to 35	Structures	-46 to 65
Infrared detectors	-200 to -80	Teflon	-240 to 204
Kapton	-269 to 400	tang camera	± 0.5 °C

Propellants also have temp req

Relationship to other subsystem

- Thermal control system affects and is affected by almost all other subsystems.

- **Power system:** typically the greatest interaction with the thermal control system
  - Accounting for all dissipated electrical energy and transferring this energy to a radiator
  - Batteries have a narrow temperature operating range (or require some special attention)

- IR (if spacecraft has one) can be a major problem for the thermal control system
  - Required to operate at temperatures in the cryogenic range, 0 – 120 K

- **Attitude control system**: determine the thermal radiation inputs from the sun and Earth.

can help control thermal control system

Thermal Environment

- **Orbital characteristics** are a major source of variation
  - Duration of eclipse
  - Solar intensity varies as the distance from the sun changes
  - Solar intensity experienced in orbit around the Earth will vary seasonally
- **Reflected solar input** to the vehicle from whatever planet it orbits, and depends on:
  - Orbital altitude
  - Planetary reflectivity or albedo → more applicable near celestial objects
  - Orbit inclination
- **Operational activities** alter the thermal environment
  - Very low orbit altitude: produce heating due to free-molecular flow
  - Onboard equipment (on/off)
  - Thruster firing
- Spacecraft surface characteristics change due to UV exposure, atomic oxygen attack, micrometeoroid/debris impact. evil, can be a significant issue for certain, especially long term missions.
- Anomalous events provides an unpredictable source of changes in thermal environment — must have tolerance for reasonable consideration
  - Failure in a wiring harness
  - Sun shade or shield may fail

Passive Thermal Control

- Thermal control systems can be classified as
  - Active / Passive / Semi-passive

- Use of **geometry**, **coatings**, **insulation blankets**, **sun shields**, **radiating fins**, and **heat pipes**

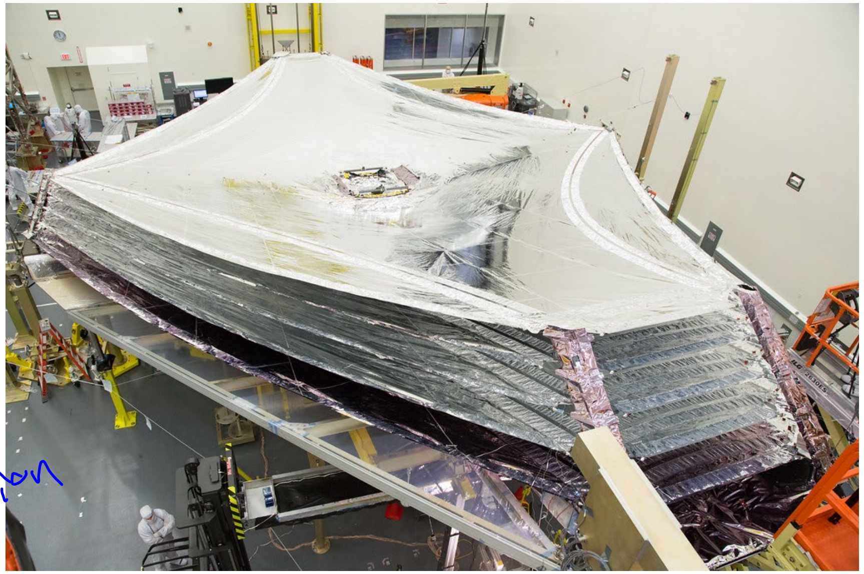
  i. <u>Geometry</u>
    - Configuring the spacecraft to provide the required thermal radiating area
    - Placing low-temperature objects in shadow → common to place on back of solar panel
    - Exposing high-temperature objects to the sun
    - Manipulation of the spacecraft to optimise thermal control

  ii. <u>Isolation blanket</u>
    - Multilayer design consisting of several layers of aluminised Mylar or other plastics, spaced with nylon or Dacron mesh
    - External coatings of fibreglass or Dacron may be used to protect against UV radiation, atomic oxygen erosion and micrometeoroid damage.

Passive Thermal Control

iii. Sun shield

- Polished aluminium (or gold) plate
- More sophisticated reflectors may used silvered Teflon (act as a second-surface mirror)



iv. Fin

- To dissipate large amount of heat or small amounts at low temperature
- Requiring a large surface area
- **Large number of fins in circular configurations**: have difficulty obtaining an adequate view factor to surface

→ shading or radiation emission/absorption interference

- **Very long fin**: limited in effectiveness by the ability to conduct heat through the fins.

limited by conduction thermal gradient

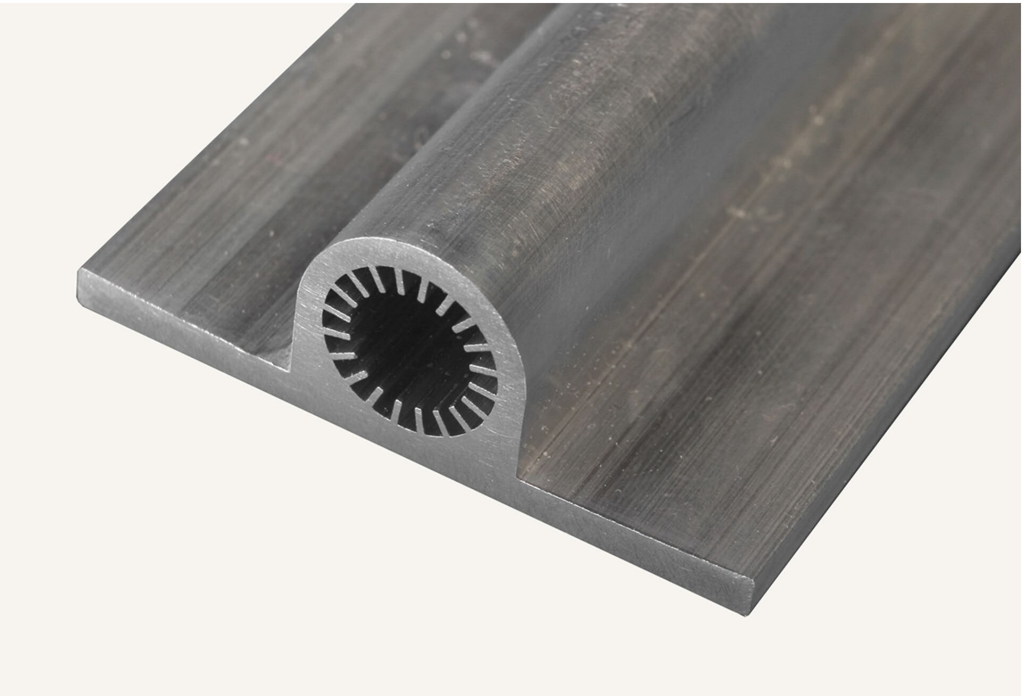
2.2 Thermal Control System Options

Passive Thermal Control

when used passively it has no control system.
• no extra energy needed

v. Heat pipe

- Tubular devices containing a wick running the length of the pipe, which is partially filled with a fluid (such as NH_3)
- Connected between a portion of the spacecraft from which heat is to be removed and a potion to which it is to be dumped.
- Simply conducts energy when there is a temperature differential and crease to do so if the differential disappears.
- Control of heat pipes is possible by mean of loaded gas reservoirs and valves.
- Need to ensure:
  - ✓ the hot end is not so hot as to dry the wick completely.
  - ✓ The cold end must not be as cold as to freeze the liquid
- Work differently in 0 gravity. → fluid mechanics cursed in microgravity.



evaporate

condense

← uses evaporation to passively move heat

Active Thermal Control

- Thermal transport may be actively implemented by pumped circulation loops.

i. Heater

- Wire-wound resistance heaters or deposited resistance strip heater
- Control my be by means of ground command and/or automatically with onboard thermostats

ii. Coolers

- Refrigeration cycles are difficult to operate in ZERO-gravity
- Thermoelectric or Peltier cooling is used

no moving parts, but really inefficient.

- Primary application: cooling of detector elements in infrared observational instruments
- **Cryostat:** expansion of high-pressure gas through an orifice. Two-stage cryostat (very low temperature, nitrogen (1st stage) and hydrogen (2nd stage))
- **For long term cooling to low temperature**: using cryogenic fluid (IR measurement)

Active Thermal Control

iii. <u>Shutter or Louvers</u>

- Most common active thermal control system
- Louver (Voyager)
- Flat-plate variety (Television and Infrared observation satellite)

changing geometry to change exposed surface absorbtance/emittance

iv. <u>Actively pumped fluid loop</u>

- Conceptually identical to the cooling system in an automotive engine
- Long history of spaceflight applications
- Tube or pipe containing the working fluid is routed to a heat exchanger in the area or region to be heated or cooled.
- Heat transfer via forced convection into the fluid
- **Working fluid**: air, water, methanol, water/methanol, water/glycol, Freon, carbon tetrachloride

Passive vs Active

whenever possible we opt to use passive

Passive:

- ✓ No power requirement
- ✓ No moving parts
- ✓ Simple (reliable)
- ✓ Low cost
- ✗ Inflexible
- ✗ Low heat transfer rates
- ✗ Performance variability (e.g. Surface coatings)

won't work in near sun environment (practically)

Active:

- ✓ Flexible and adaptive
- ✓ High heat transfer rate
- ✗ Power required
- ✗ Mechanisms / moving components (reliability)
- ✗ Mass
- ✗ High(er) cost (e.g. fluid loop systems)

active only used when absolutely needed.

2.3 Design Methodology

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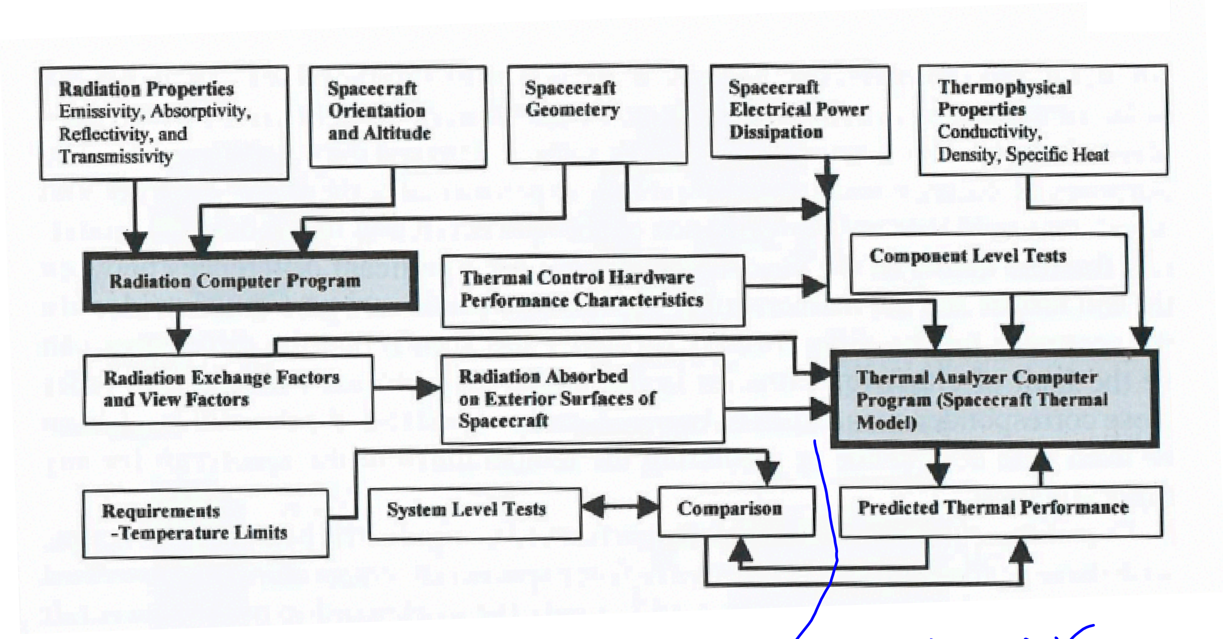
Design Principles

tests need to cover worst case scenarios

1. Temperature limits of **all spacecraft components** must be categorised by the thermal control group with inputs from almost all other spacecraft engineering groups.
2. Establish thermal boundary conditions for the mission
    - Determined from the mission analysis group (attitude and orientation for all mission phase) and the power group (electrical power dissipation in all electrical components)
3. Define temperature limits and understand other requirements
4. Start the design using analytical tools
    - Radiation program (Define the absorbed energy on the spacecraft external faces)
    - Generalised thermal analyser



compared for differences which indicate errors. (potentially in both)

NOTE:

System-level thermal tests are required: Solar balance test and thermal vacuum test

Conduction

describes heat transfer in a solid.

- Fourier's law: $\vec{q} = -\kappa \nabla T$

where $\vec{q}$ = heat flux, W/m^2
κ = material conductivity, W/m K

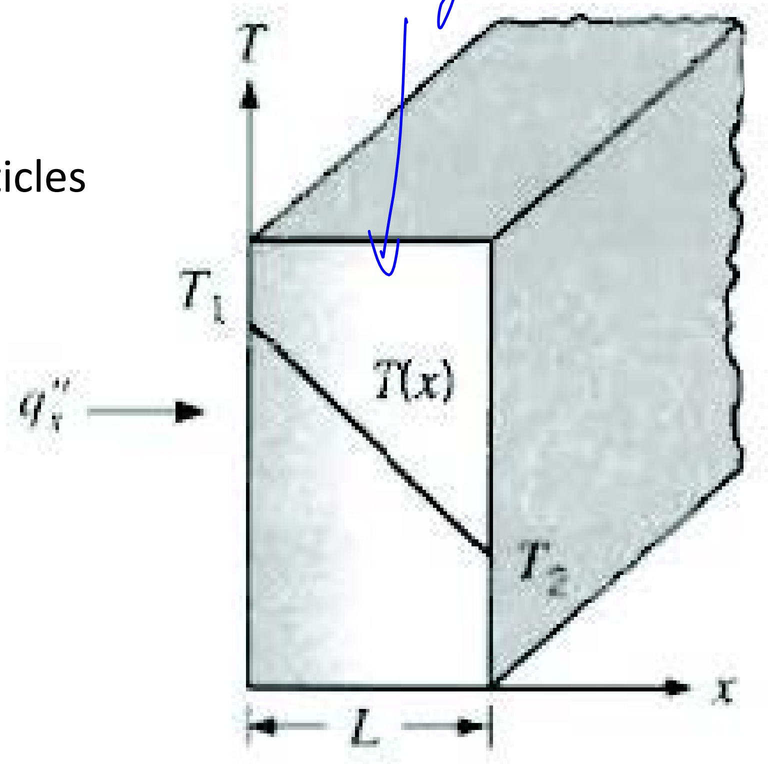
- Dominant heat transfer in a solid (microscopic diffusion and collision of particles

- For steady-state heat conduction in rectangular coordinates and 1D:

$$Q = \left(\frac{\kappa A}{\Delta x}\right)(T_1 - T_2)$$

where Q = energy transfer rate, W
A = area normal to the heat transfer direction, m^2

linear thermal gradient.



Radiation

- All matter radiates electromagnetic energy in the form of “small bundles of energy” (Photons)
- Photon: travel at the speed of light and have zero mass
- Total energy per unit time per unit surface area, q (W/m^2) is given by

$$\boxed{q = \varepsilon \sigma T^4}$$

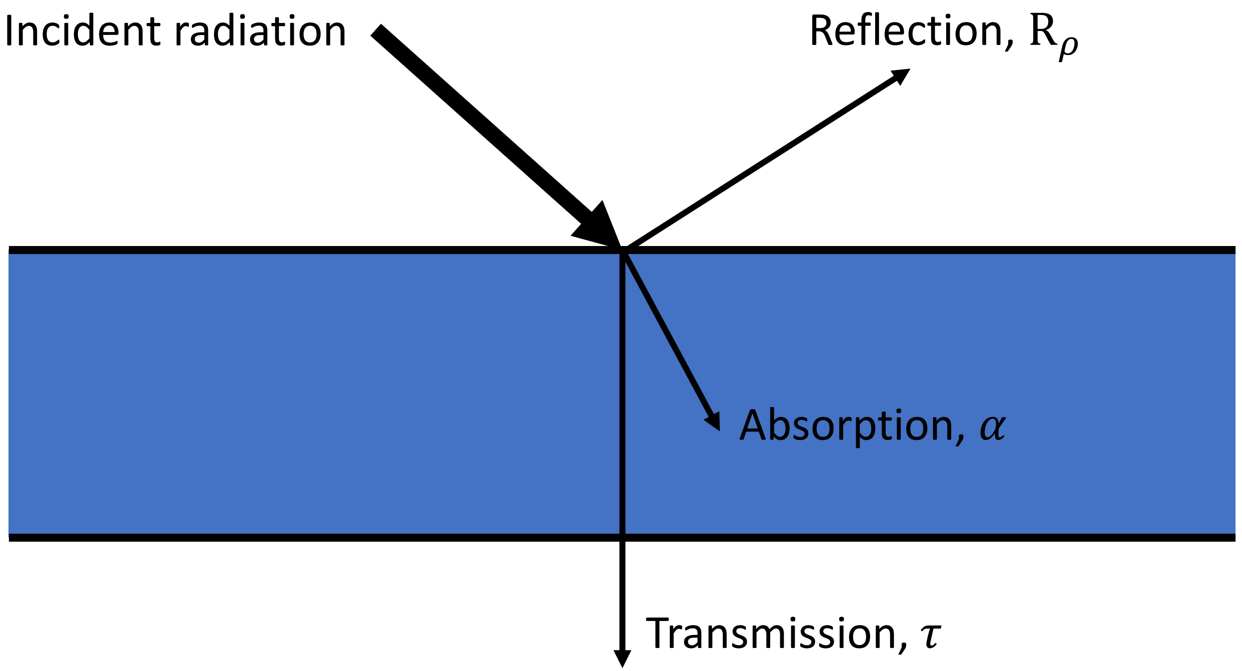
where ε= emissivity
σ = Stefan-Boltzmann constant,
$5.67 \times 10^{-8} \left[\frac{W}{m^2 K^4}\right]$

- **Emissivity:**
  - Dimensionless thermophysical property (0 ~ 1)
  - Perfect emitter: 1 (blackbody)
  - E.g. Polished gold or silver surface (~ 0.05)

- Surface also absorb photons.
  - Uniform temperature: absorption of photons = emission of photons

- **Kirchhoff’s Law:** For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity (emissivity ε = absorptivity α)

Radiation



$$\alpha + R_\rho + \tau = 1$$

2.4 Basic Analytical Equations and Relations

Radiation

- Consider the radiant energy emitted from a surface:
  - Monochromatic radiation energy (Radiation energy at given wavelength) emitted form the surface of blackbody is

$$\boxed{\mathrm{E}_{b\lambda} = \frac{C_1\lambda^{-5}}{\left(e^{\frac{C_2}{\lambda T}} - 1\right)}}$$

where $E_{b\lambda}$= monochromatic emissive power (energy per unit time per unit area per unit wavelength)

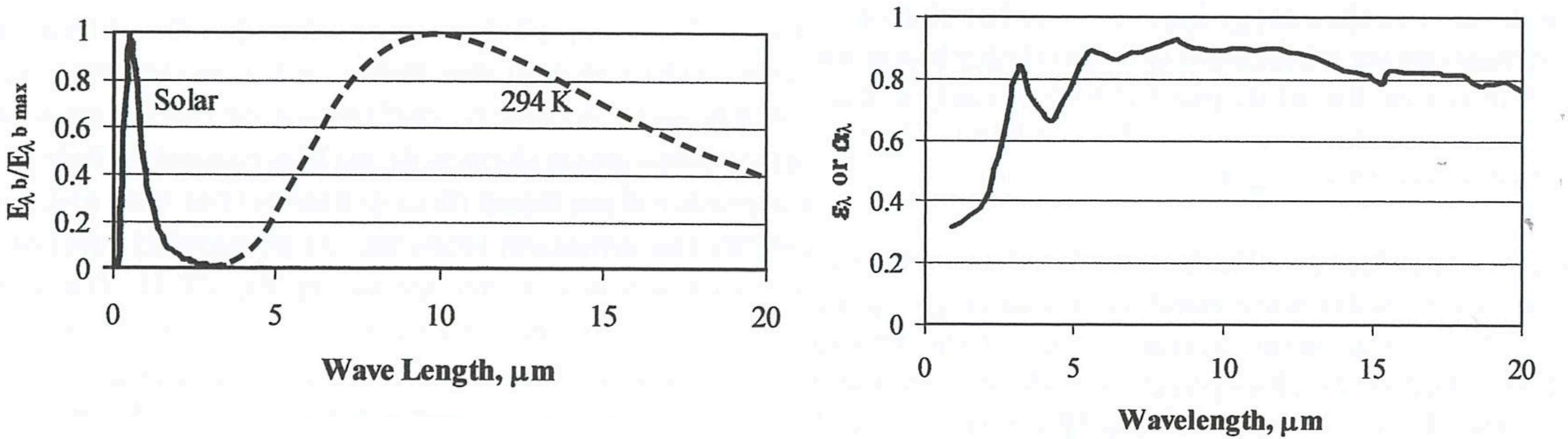
λ = Wavelenggh,

C1 , C2 = constants

  - For non-blackbody, the monochromatic emissivity ε_λ must be considered
  - Total emission from surface is

$$\boxed{q = \int_0^\infty \frac{\varepsilon_\lambda C_1\lambda^{-5}}{\left(e^{\frac{C_2}{\lambda T}} - 1\right)} d\lambda}$$

Radiation



Thermal performance of white painted surface with solar input

Q: Explain why a white painted surface exposed to solar radiation in space will remain a relatively low temperature

$$q_{absorbed} = \int_0^\infty \frac{F\alpha_\lambda C_1 \lambda^{-5}}{\left(e^{\frac{C_2}{\lambda T}} - 1\right)} d\lambda$$

$$q = \int_0^\infty \frac{\varepsilon_\lambda C_1 \lambda^{-5}}{\left(e^{\frac{C_2}{\lambda T}} - 1\right)} d\lambda$$

Selective surfaces

- **Selective surfaces:** surfaces with radically different emissivity (or absorptivity) values in the solar wave band as compared to the IR wave band
- **Solar absorptivity, α_s:** mean average value of absorptivity over the solar wave band
- **IR emissivity, ε_{IR}:** mean average value of emissivity over the IR wave band
  - Weak function of surface temperature
  - The temperature must be few hundred degrees different from room temperature to show a significant change from the room temperature

- Most spacecraft thermal analyses are performed using α_s and ε_{IR}
- Selective surface will produce the lowest temperature when irradiated by solar energy in space is an **optical solar reflector**
  - Substrate with a highly reflective surface
  - Overlaid with a transparent cover

- Highly reflective surfaces: Metallic surfaces (but metallic surfaces exhibit relatively low emissivities)

Surface Temperature Prediction

- Surface with an IR emissivity of 0.8 and a solar absorptivity of 0.15 is perfectively insulated on the back side, placed in space, and irradiated with solar energy normal to the surface. Find the temperature (Solar flux value: 1371 W/m^2)

Radiator Temperatures

- Estimate the temperature of insulated surfaces with solar heating.
  - θ = Angle between the solar vector and the surface normal vector of the insulated surface.
  - A_R = Radiator area, m^2
  - Q_W = Waste heat rejected by the radiator, W
  - α_s = solar absorptivity
  - ε_{IR} = IR emissivity

View Factors

- The expression for the net radiation exchange Q_{net} between two surfaces that are perfect emitters ($\varepsilon = 1$) and perfect absorbers ($\alpha = 1$), that is, black surfaces, is given by:

$$\boxed{Q_{net,1\to2} = A_1 F_{1\to2}\sigma(T_1^4 - T_2^4)}$$

$$\boxed{Q_{net,2\to1} = A_2 F_{2\to1}\sigma(T_2^4 - T_1^4)}$$

where, A = Area

T = Absolute surface temperature

F = view factor

$\equiv$ Fraction of the radiant energy directly incident on a receiving surface relative to the total radiant energy leaving the sending surface

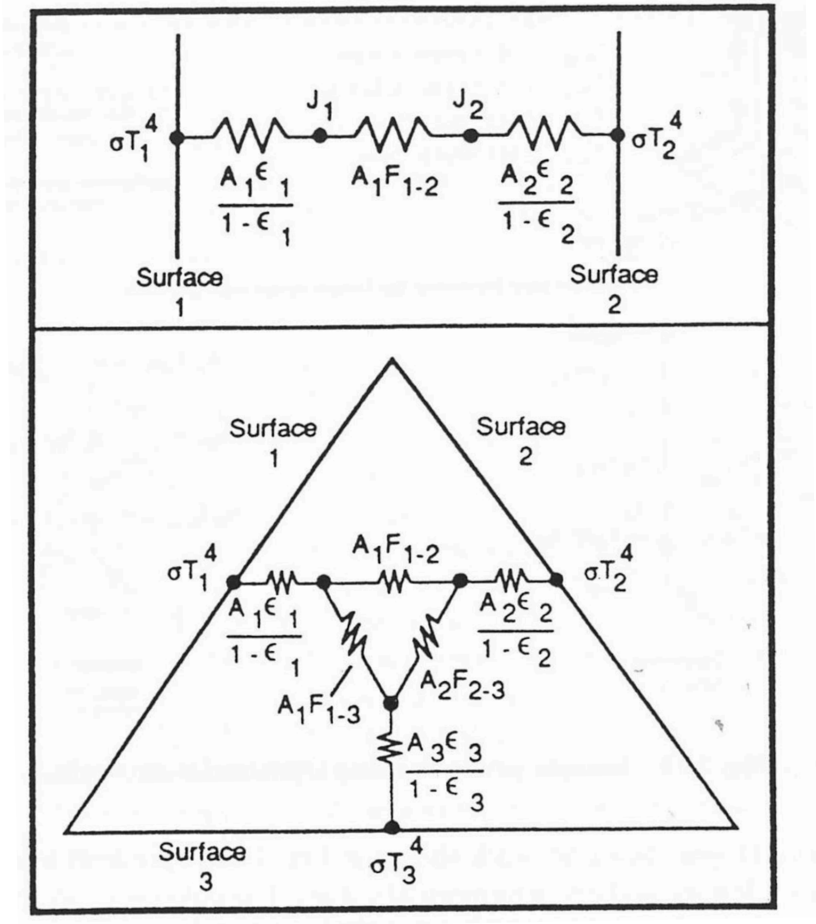
NOTE:

- Sum of all the view factors from a surface must equal 1
- Reciprocity rule: $A_x F_{x\to y} = A_y F_{y\to x}$

- Some example of the view factor calculation can be found from NACA TN 2836 (which is in the module BB)

Oppenheim Radiation Networks

- $Q_{net,2\rightarrow1} = A_2F_{2\rightarrow1}\sigma(T_2^4 - T_1^4)$ provides a means of calculating radiant energy exchange between ”black” surfaces.



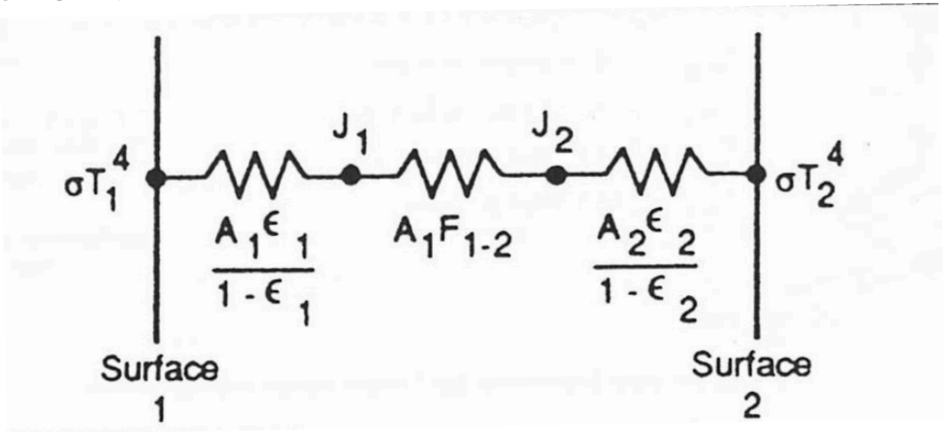
Determining radiation exchange between non-black surfaces:

“**Oppenheim Radiation Network**”

1. All surfaces are “gray”
   - All surface emissivities are constant over the wavelength bands applicable to the operating temperature
2. All surfaces emit and reflect diffusely
   - Most surfaces can be considered diffuse except for shiny metallic surfaces
3. All surfaces are isothermal
4. The radiosities are uniform across each surfaces
   - Radiosity is defined as the toral radiant energy striking a surface including emitted, reflected, re-reflected, …)

Oppenheim Radiation Networks

- **Characteristics of the Oppenheim network:**

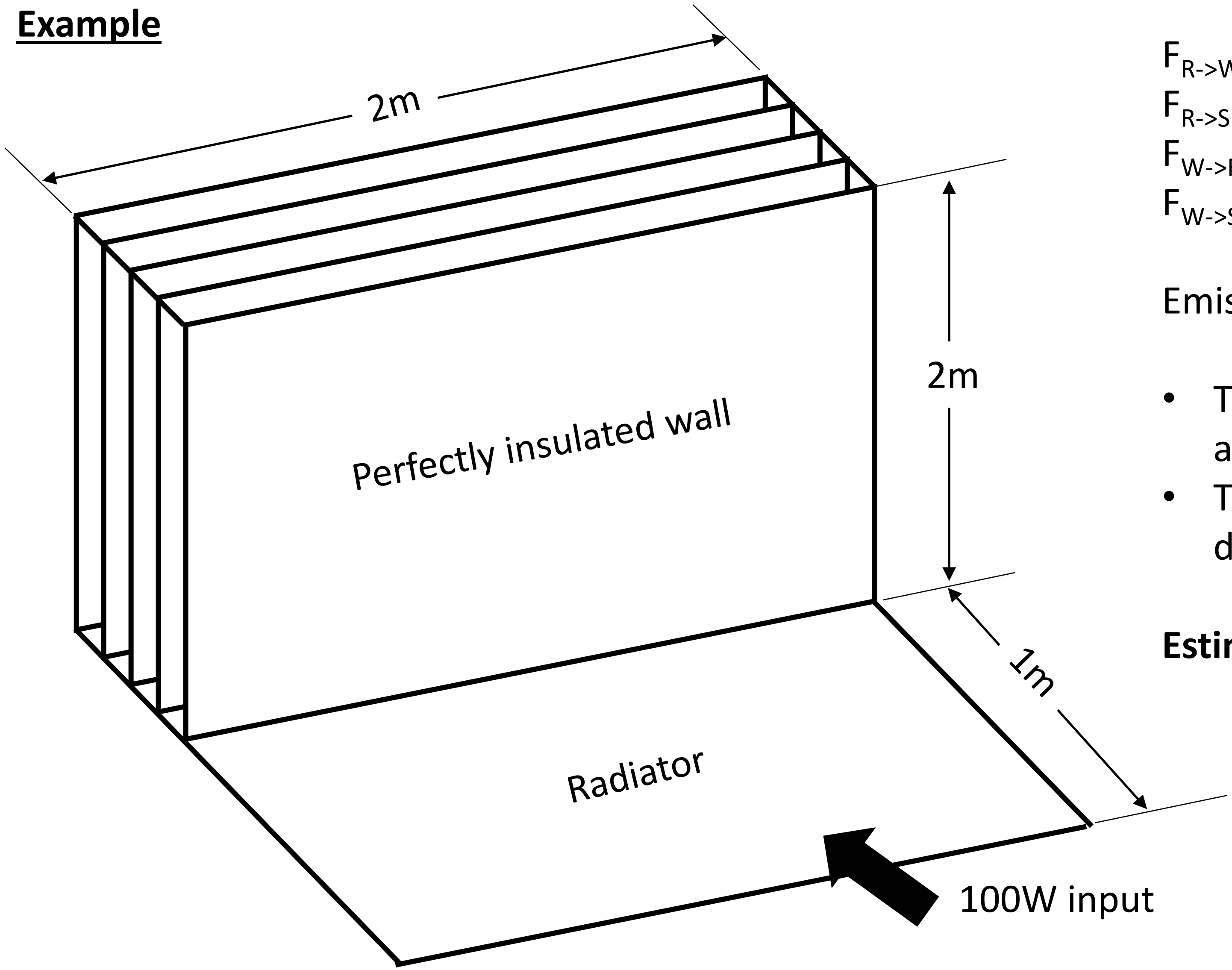


  - At each give surface, x, the adjacent conductor is of the form: $\frac{\varepsilon_x}{1-\varepsilon_x}A_x$
  - The conductor is connected between the surface node and the dummy J_x node.
  - The potential at the surface node is $\sigma(T_x)^4$ and $\sigma\left(T_J\right)^4$ at the J node.
  - The network is completed by connecting each J node to every other J node.
  - The conductors connecting the J nodes are of the form $A_x F_{x\to y}$
  - <u>**NOTE:**</u> if a given surface is perfectly insulated or if the emissivity of the node is one, conductor $\frac{\varepsilon_x}{1-\varepsilon_x}A_x$ is eliminated. Thus, the surface potential moves to the J node location

<u>More details of Oppenheim radiation network method can be found his paper in the module BB)</u>

Oppenheim Radiation Networks

Example



$F_{R\text{->}W}$ = 0.29 (Radiator to wall)
$F_{R\text{->}S}$ = 0.71 (Radiator to space)
$F_{W\text{->}R}$ = 0.145 (Wall to Radiator)
$F_{W\text{->}S}$ = 0.855 (Wall to Space)

Emissivity of surfaces = 0.8

- The is showed from the sun, unaffected by Albedo and Earth IR radiation
- The radiator and wall see only each other and deep space

Estimate the temperatures of radiator and wall.

Combined Radiation and Conduction Thermal Networks

- Conduction heat-transfer problem are also commonly modelled using thermal networks
- **Potential at node**: temperature to the first power
- **Conductor value:** multiplied by the temperature difference in the steady-state conduction equation
  - Example: $\kappa \frac{A}{\Delta x}$ for rectangular geometry

- For most spacecraft thermal control problem, conduction and radiation heat transfer modes are interrelated

  ➡ Coupling of conduction and radiation

- Problem with combining the two network:
  - Potentials are vastly different (conduction: first power of temperature / radiation: fourth power of temperature)
  - Need to manipulating the radiation relationship
  - Radiation conductor values:

$$\frac{\varepsilon_x}{1-\varepsilon_x} A_x \sigma\left[\left(T_x^2+T_y^2\right)\left(T_x+T_y\right)\right] \quad \text{or} \quad A_x F_{x\to y} \sigma\left[\left(T_x^2+T_y^2\right)\left(T_x+T_y\right)\right]$$

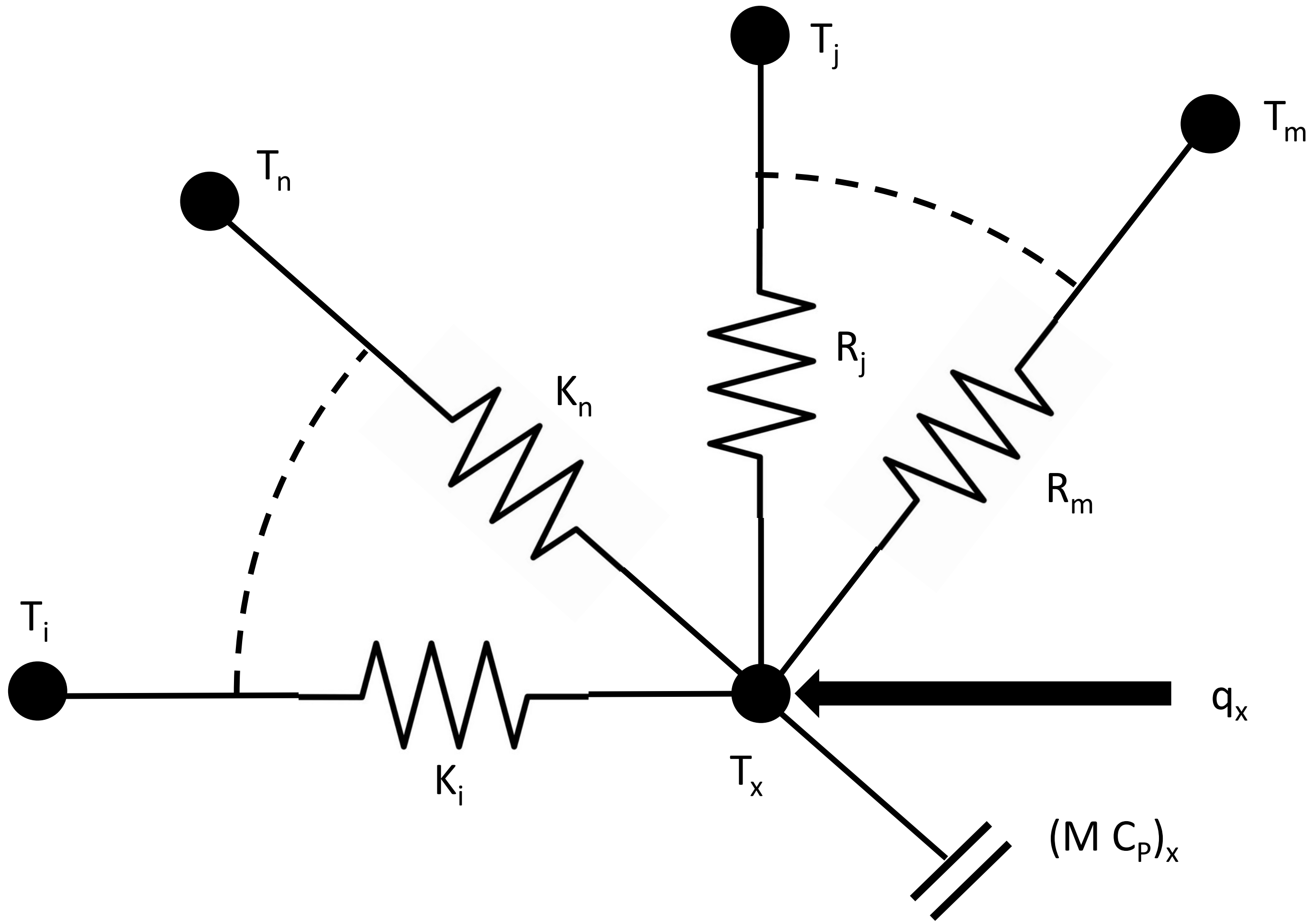
Generalised Thermal Networks

- The steady-state networks can be extended to include transient conditions.
  - Difference (Steady-state and transient cases) is adding a **thermal capacitance** at the node point

- **Node:** Representing finite volumes or pieces of the physical thermal system
- **Thermal capacitance of node**: (node mass) x (specific heat of the node material)

- Two formulation methods:
  1. **Explicit solution:** Allows a step-by-step application of the equation at each node until all nodes are updated and the time step is completed
     - The size of the time step is limited to a critical time step
  2. **Implicit solution:** Needs the inversion of a matrix involving all of the nodes at each time step.
     - No limit on the time step. Generally not exceeding the explicit critical time step by more than a factor of two or three in order to maintain accuracy.
- Steady-state solutions are readily analysed using the given transient equations by merely continuing the computations until the temperature no longer change.

Generalised Thermal Networks



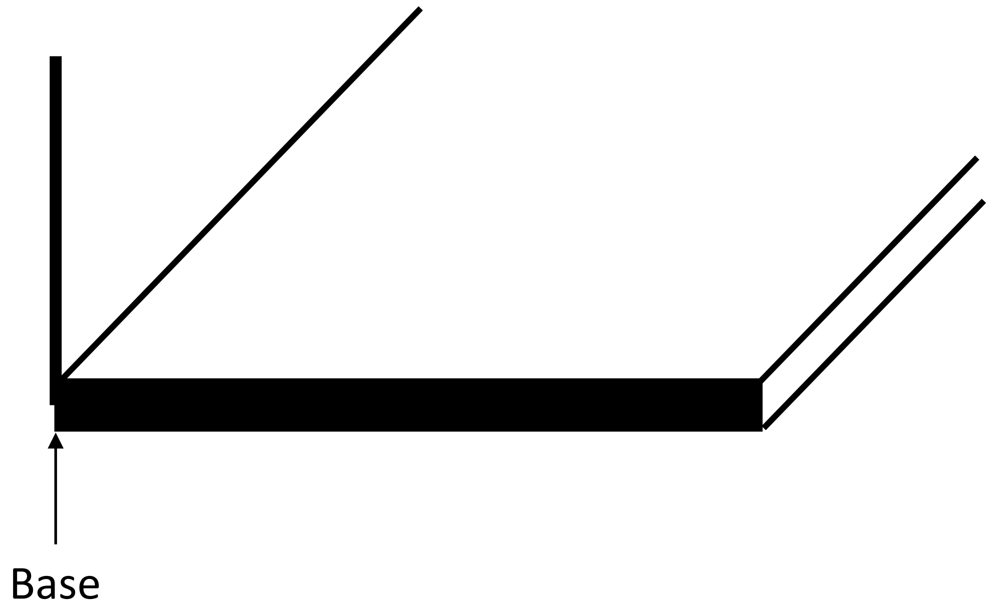
Generalised Thermal Networks

Example (Space radiator fin)

The aluminium fin is 30 cm wide, 0.2 cm thick, and 1 m long.

The left edge of the fin is maintained at a constant temperature of 340 K by the radiator's working fluid.

- κ = 150 W/(m K)
- C_p = 0.879 J / (g K)
- ρ =. 2.643 g/cm^3
- C (thermal capacitance) = mass x specific heat
- K (thermal conductance) = conductivity x Area / distance



- Bottom side of the fin (base) is perfectly insulated.
- Top is exposed to deep space and solar heating.
- Solar vector is assumed to be normal to the radiator surface
- Surface property: solar absorptivity = 0.2 / IR emissivity = 0.8

Estimate the temperature of a fin in terms of time.

Preliminary Design Approach

- Fist-order estimation of the thermal performance of a spacecraft.
- Bound the spacecraft thermal design and provide a basis for estimating the engineering and computer time required to develop the detailed spacecraft thermal design.
- **Procedures:**
  1. Estimate temperature limits
  2. Establish electrical power dissipation
  3. Determine the diameter of a sphere whose surface area is equal to total outer surface area of actual spacecraft.
  4. Select radiation surface property values
  5. Compute spacecraft worst-case hot temperature
  6. Compute spacecraft worst-case cold temperature
  7. Compare worse-case hot and cold temperature with temperature limits
  8. Required area for body mounted radiator
  9. Radiator temperature for worst-case cold conditions
  10. Heater power required to maintain radiator at lower limit
  11. Determine if there are special thermal control problems.
  12. Estimate subsystem weight, cost, and power / 13. Documentation

Question 1

A planet visible albedo is approximately 0.1 and thermal emissivity of the surface of the planet is 0.87. The average intensity of solar radiation is 1270 W/m^2 at the surface of the planet. Assume the planet is a perfect sphere. Estimate the average surface temperature of the planet.

- 283.2 K
- 275.9 K
- 292.1 K
- 486.5 K
- Cannot calculate because of missing information

285.0 K
350.4 K
403.1 K

Quiz 2

Question 2

A satellite uses two solid aluminium spheres as calibration sources for optical measurements. The spacecraft ejects the spheres and images them after their temperatures have stabilized. One is painted in black, and other is vapor-deposited aluminium. The spheres are ejected at 300 °C, and each is continually exposed to the Sun afterwards. Assume Q_{sun} = 1353 W/m^2 and the solar absorptance and IR emittance of the surface of a sphere painted in black are 0.94 and 0.85, respectively. The solar absorptance and IR emittance of the surface of a vapor-deposited aluminium sphere are 0.16 and 0.07, respectively. Assume the solar radiation is the only external heat source. **Find the steady-state temperature of a sphere painted in black**. Ignore the interactions of spheres.

- 180.3 K
- 231.8 K
- 285.0 K
- 350.4 K
- 403.1 K

285.0 K
350.4 K
403.1 K

Quiz 2 Review

Question 3

Long-range sensors determine a re-entry capsule is emitting 50,000 W/m^2 of energy and absorbing 4,000 W/m^2 of energy during its reentry. If the emissivity of the capsule's surface is 0.7 at wavelength corresponding to the temperature in the range of 550K ~ 2000K. Estimate its surface temperature? Stefan-Boltzmann constant is 5.67 x 10^{-8} [W m^{-2} K^{-4}]

- 563.43 K
- 916.47 K
- 1059.43 K
- 1080.01 K
- 1723.24 K

Quiz 2

Question 4

Select **ALL** parameters that can affect the **average temperature** of a spherical micro-satellite operating at LEO

- Solar radiation intensity
- Earth albedo
- IR emissivity of the satellite's surface material
- Solar absorptivity of the satellite's surface material
- Orbit inclination and orbital altitude

285.0 K
350.4 K
403.1 K

Quiz 2

Question 5

The space shuttle will use high-temperature reusable surface insulation tiles to protect the bottom of the spacecraft during the re-entry. The tiles are coated with a black borosilicate glass which has an emittance value of 0.9 and covers the areas of the vehicle where temperatures reach up to 1400 K. The thermal conductivity of the tile is 0.39 W/m·K and constant during the re-entry. Conduction will be the most significant means of heat transfer within the insulation tile. The insulation tiles should prevent heat transfer to the underlying obiter aluminium skin and structure to be below 4000 W/m2. The temperature of underlaying obiter aluminium skin should be below 550 °C. Calculate the required minimum thickness of the insulation tile

- 0.1095 m
- 8.288 cm
- 0.2125 m
- 14.43 cm
- 5.626 cm