Thermal Design for Spaceflight
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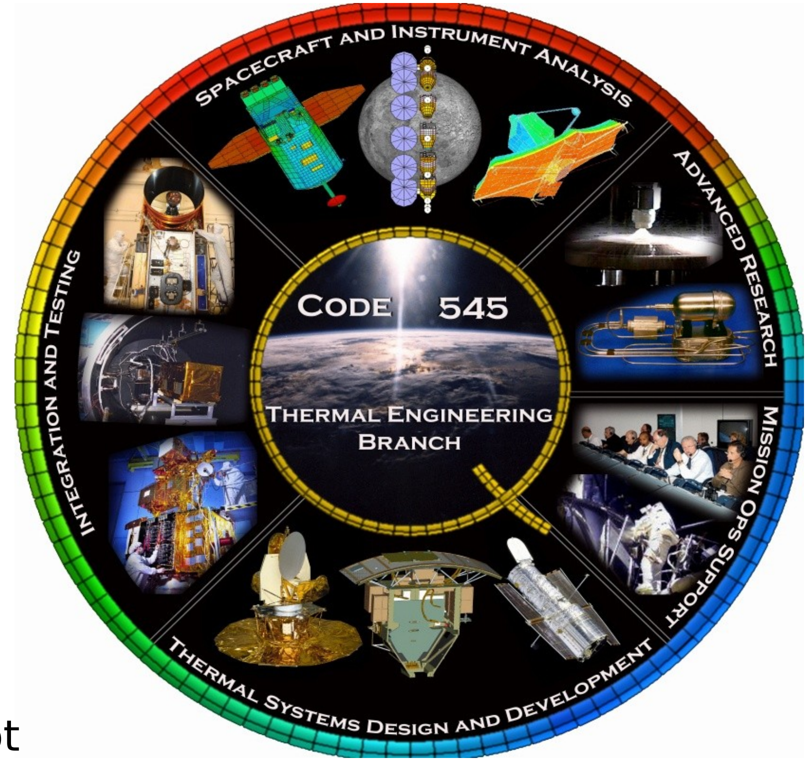


Foreword

- This package describes the Thermal Design process used at the NASA Goddard Space Flight Center
- A Thermal Analysis package can be found at ntrs.nasa.gov under the title "Thermal Modeling and Analysis"
- ***Any reference to a particular vendor's hardware or software should not be considered as an endorsement of any particular tool by NASA or the United States Government***
- The illustrations of hardware and/or software capabilities are meant to be informational and other products may have similar or superior capabilities

Thermal Design and Analysis Agenda

- **Architectures for Space Flight Design**
- **Thermal Engineering**
- **Thermal Design**
  - *Challenges of Designing for Operation in Space*
  - *Heat Transfer Basics Review*
  - *Thermal Design Process*
    - *Gathering Thermal Requirements*
    - *Available Thermal Components*
    - *Determining the Thermal Design Architecture*
    - *Early Thermal Design Calculations*
      - *Radiator and Heater Sizing*
      - *Hand Calculation estimates*
    - *Thermal Accommodation Requirements*

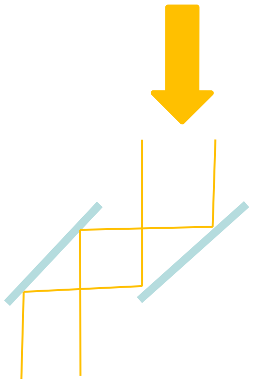
Space Flight Designs

Common Spacecraft Architectures

- Many spacecraft utilize heritage designs to reduce the risk and cost associated with developing new technology
- High level functions of all spacecraft include:
  - Fitting into the launch vehicle, surviving the launch, and deploying into an operational configuration
  - Self contained power generation capabilities
  - Acquisition and storage of science data
  - Communication with operators on the ground
  - Maintaining Pointing and Location in orbit
- The next slides go through the subsystems common to nearly all spacecraft

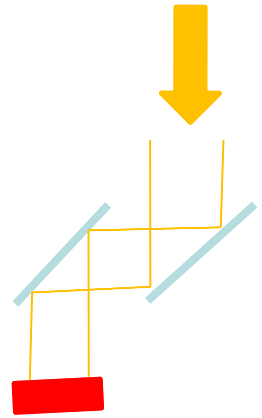
Typical Spacecraft Subsystems

- Optics – *reflect the incoming light where we want it*



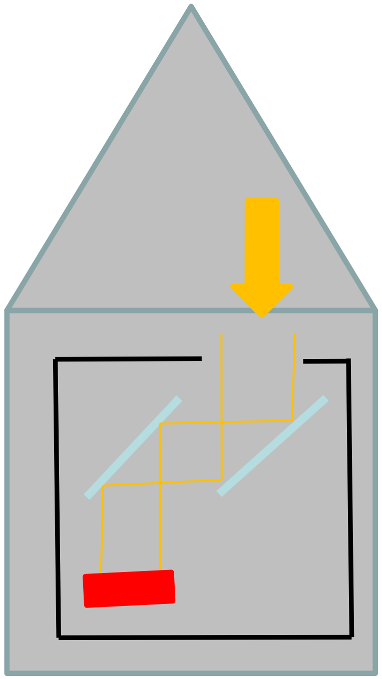
Typical Spacecraft Subsystems

- Detectors – *convert incoming light into electrical signal*



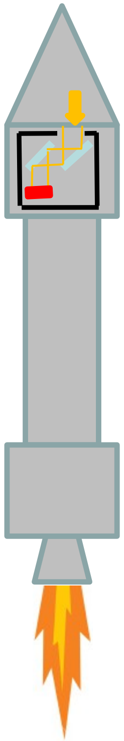
Typical Spacecraft Subsystems

- Mechanical – *make sure everything fits into the rocket*



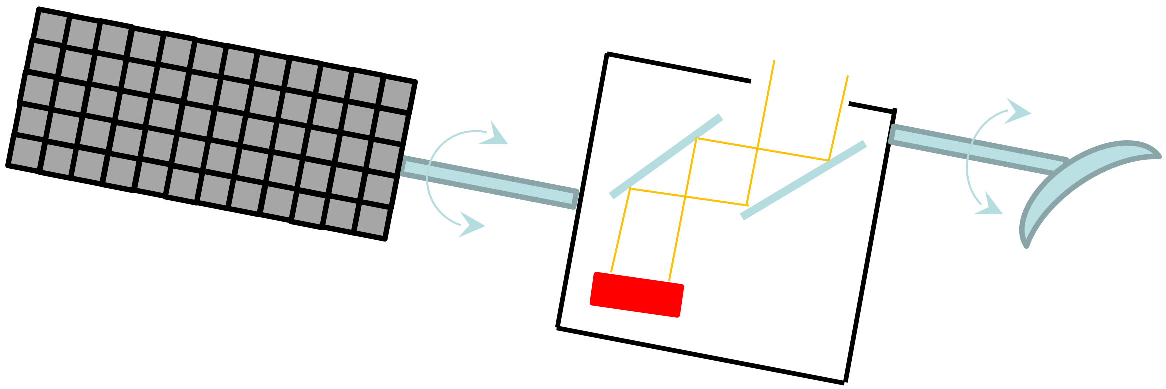
Typical Spacecraft Subsystems

- Structural – *make sure it survives the rocket ride*

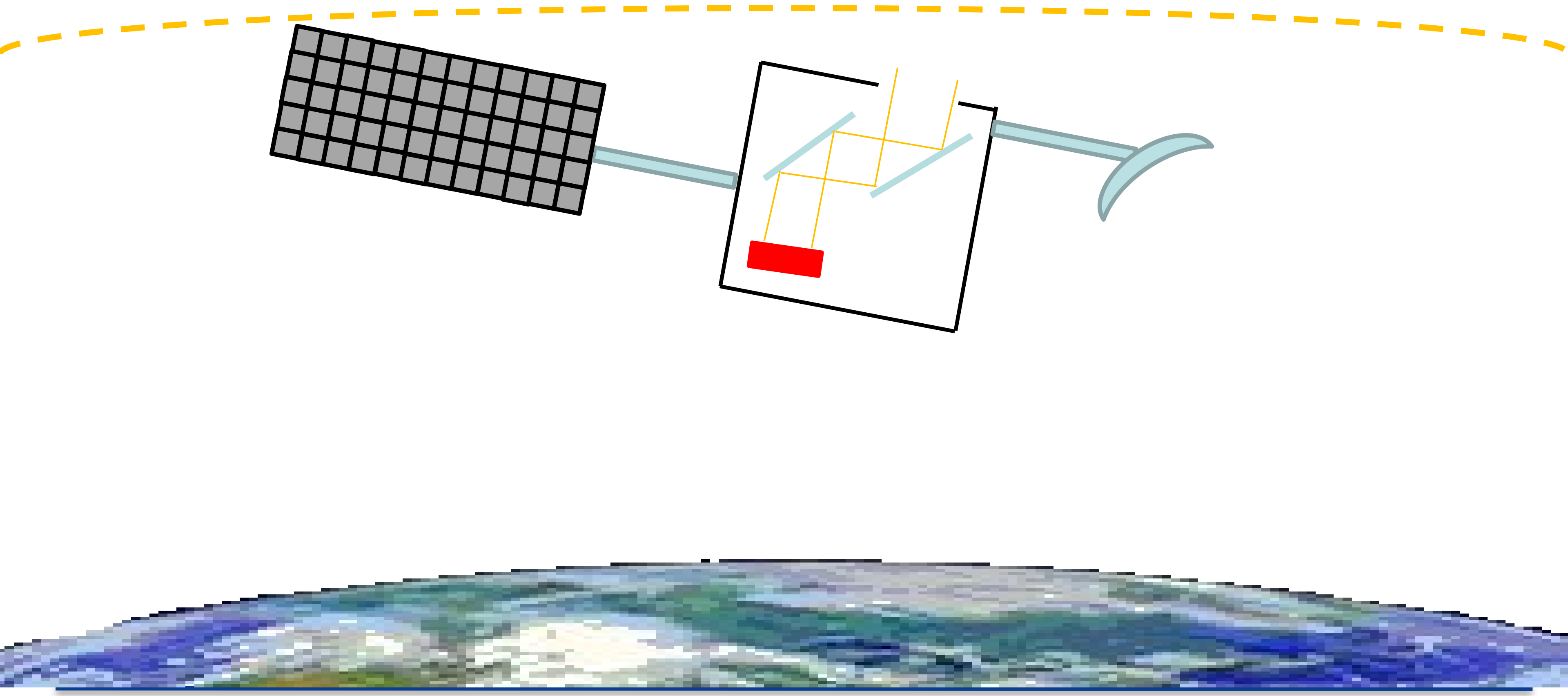


Typical Spacecraft Subsystems

- Mechanisms – *moving parts (Solar Arrays, Antenna Dishes)*

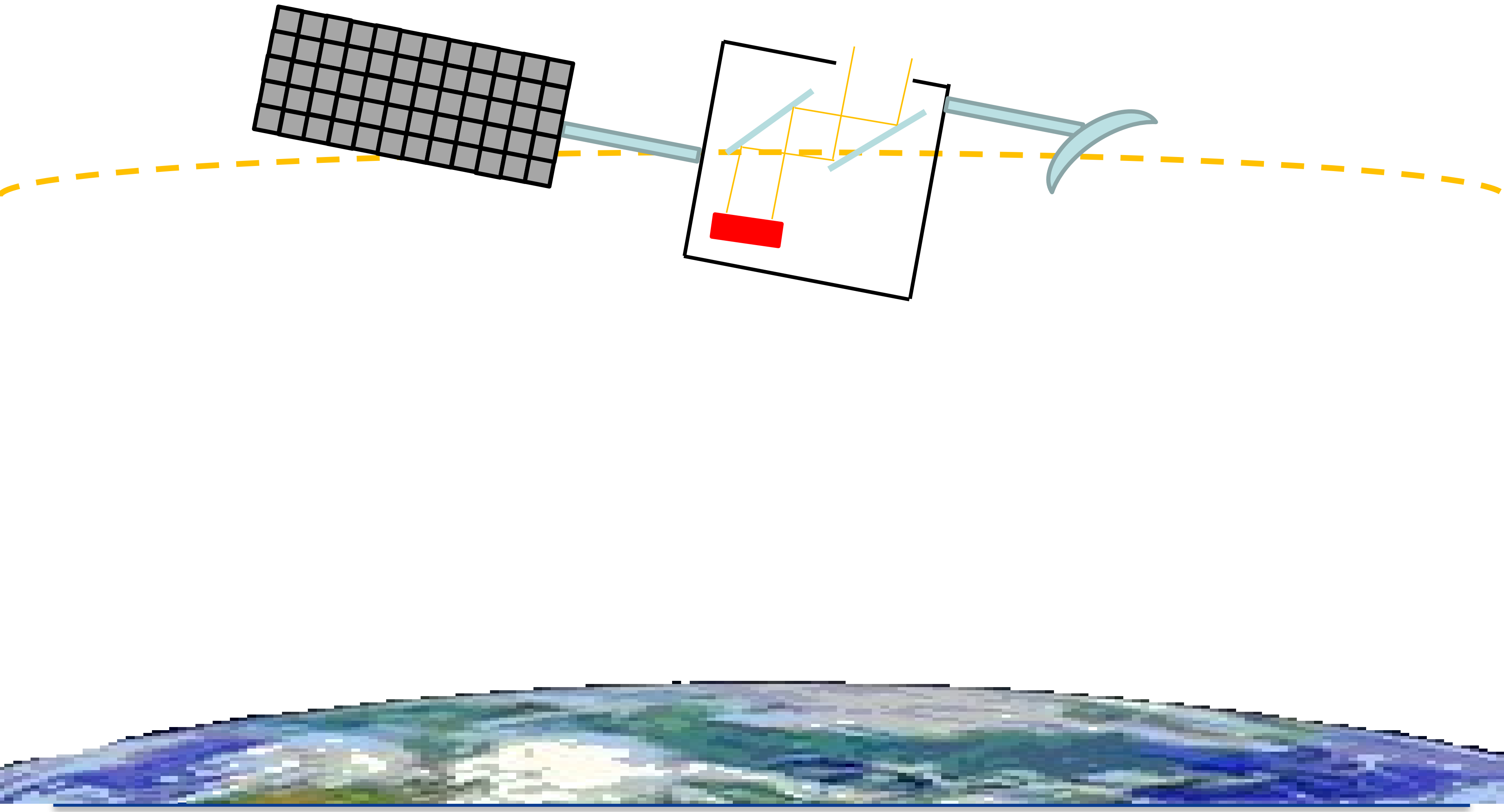


Typical Spacecraft Subsystems



Typical Spacecraft Subsystems

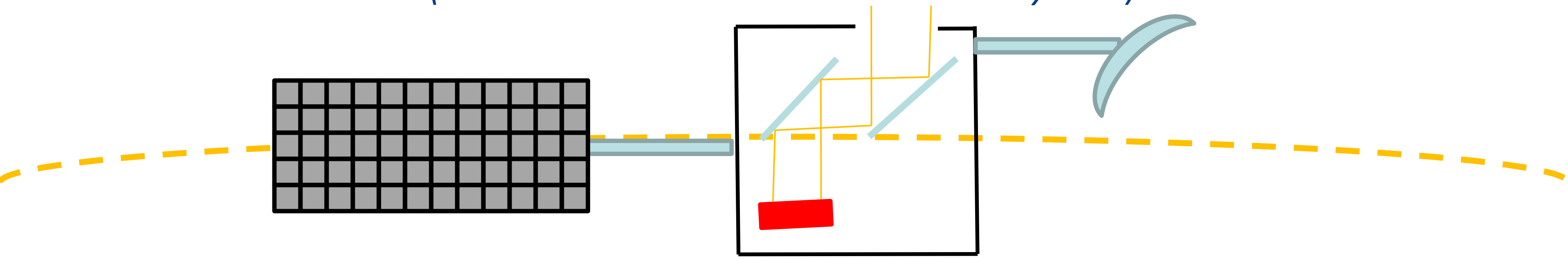
- Propulsion – *make sure we are in the right orbit*



Typical Spacecraft Subsystems

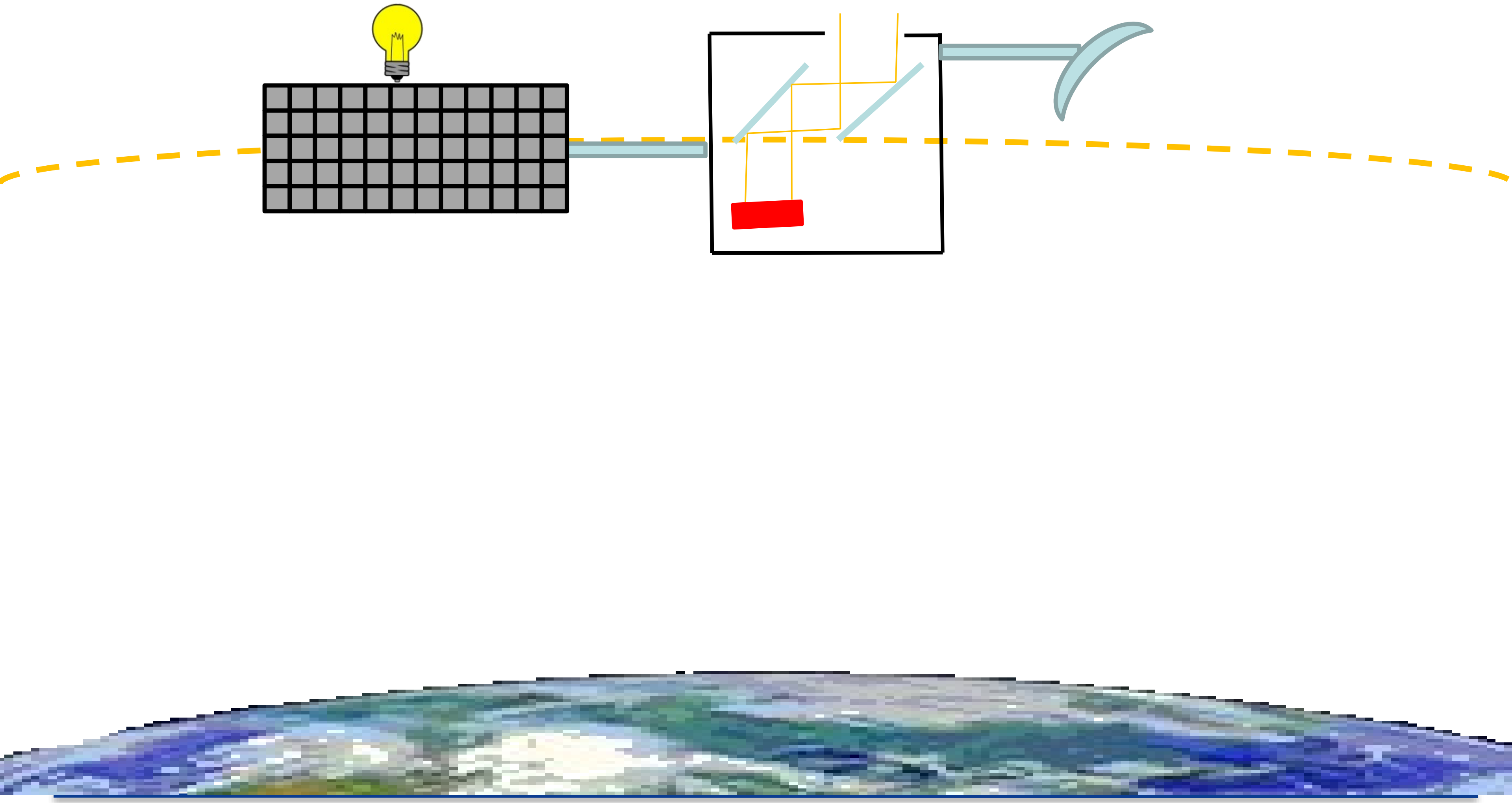
- Guidance Navigation and Control – *make sure we're pointing where we want*

(Also known at ACS: Attitude Control System)



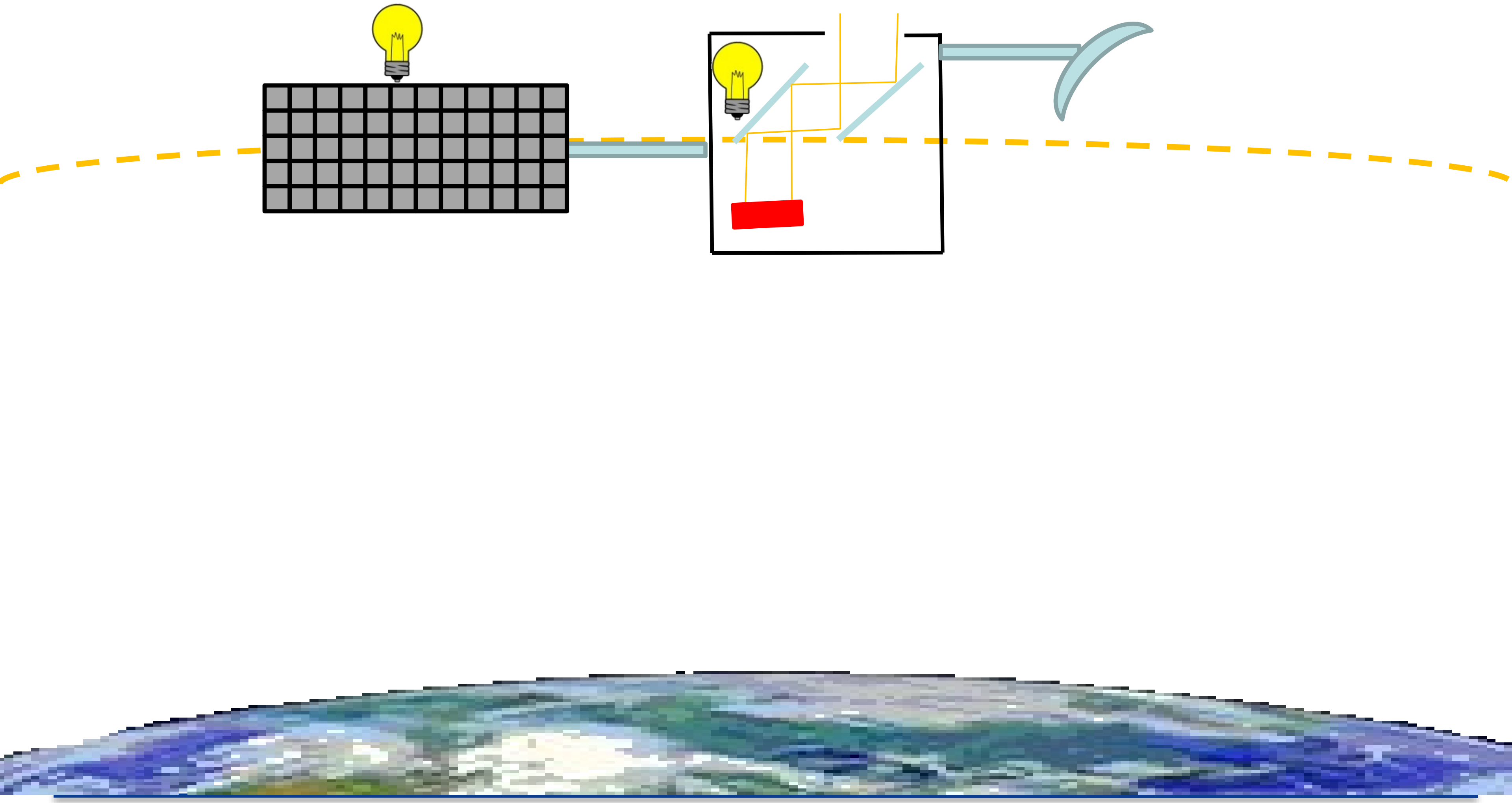
Typical Spacecraft Subsystems

- Power – *give us electrical power*



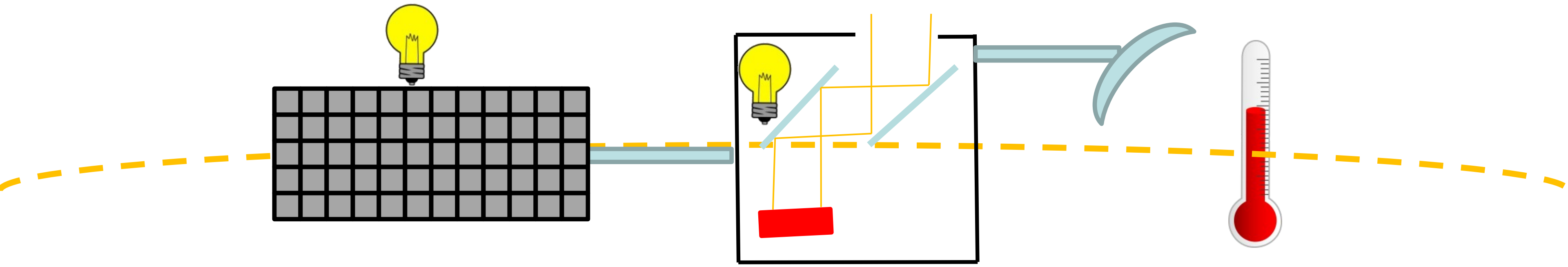
Typical Spacecraft Subsystems

- Harness – *all the wiring on the spacecraft*



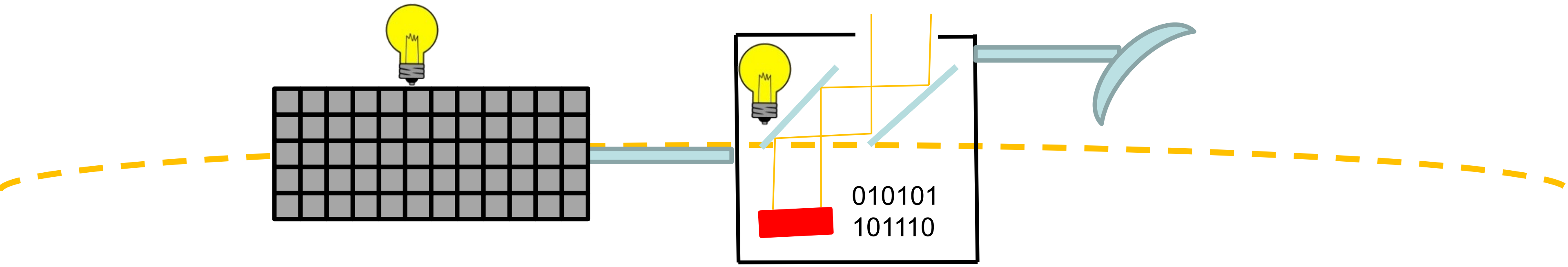
Typical Spacecraft Subsystems

- **Thermal – *make sure we don't get too hot or too cold***



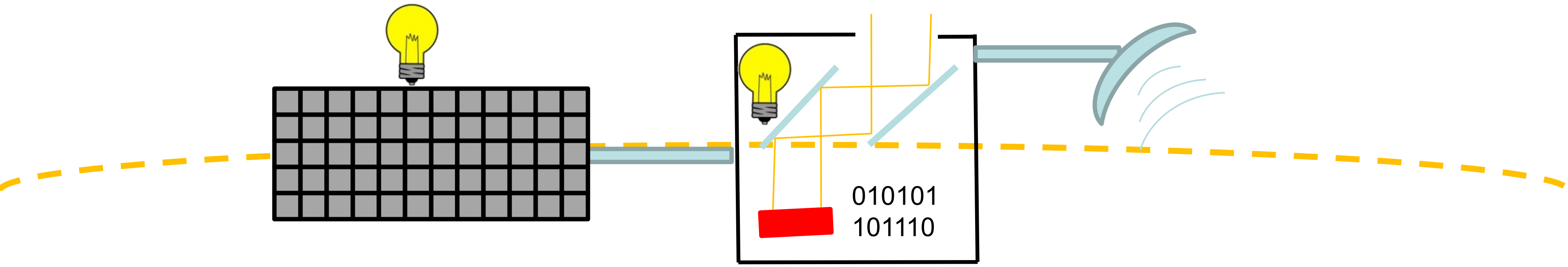
Typical Spacecraft Subsystems

- Electronics – *make sure all the data is being processed and stored*



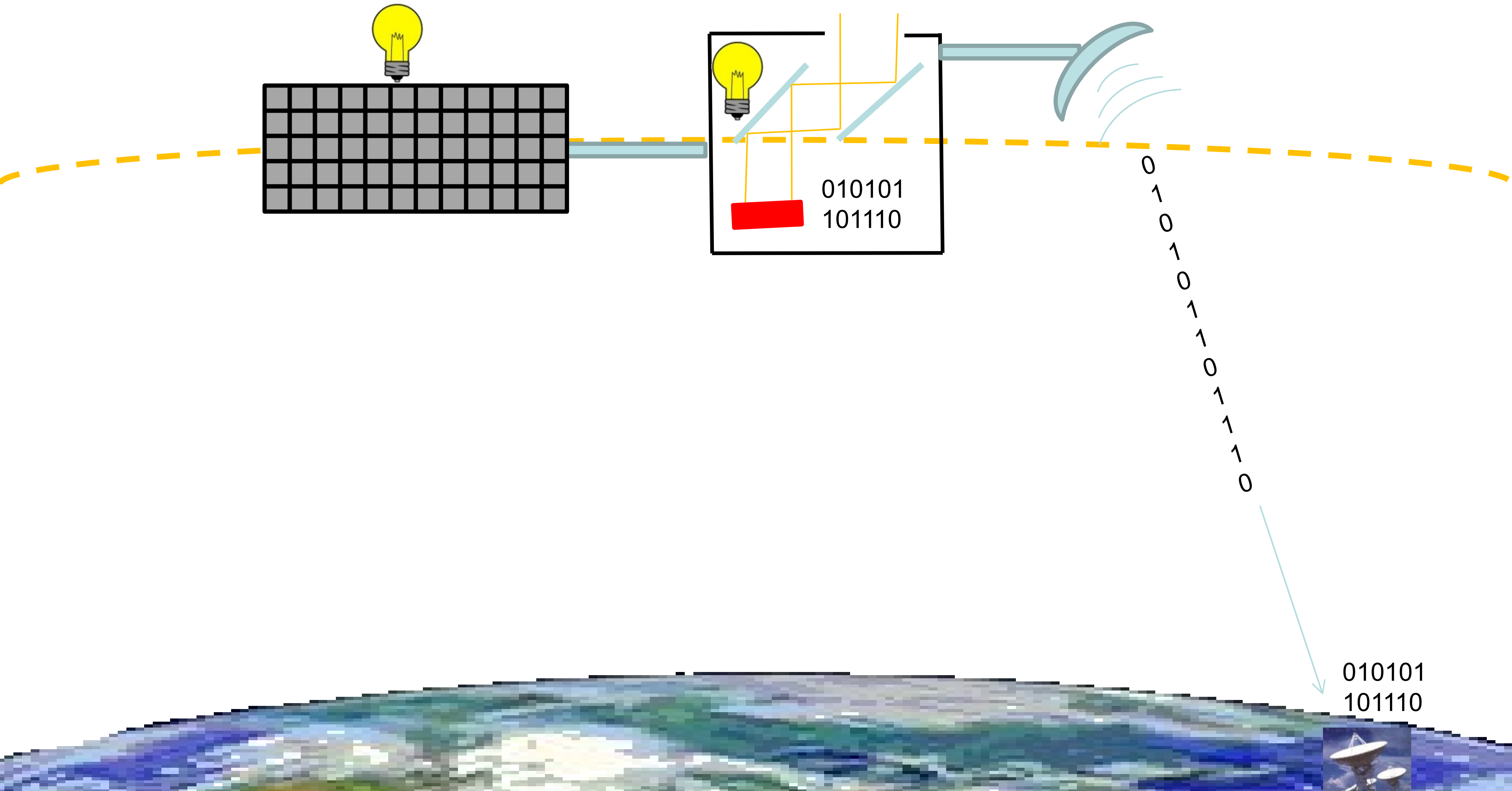
Typical Spacecraft Subsystems

- Communications – *allow us to "talk" to the spacecraft*



Typical Spacecraft Subsystems

- Flight Software – *make sure everything can talk and respond to commands*



Thermal Engineering

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Thermal Engineering

- *Thermal Engineering is the management of energy to maintain components within optimum performance thermal limits to satisfy requirements. It encompasses the product life cycle from early concepts through operations:*
  - **Design** – *the determination of what thermal hardware is necessary to meet requirements*
  - **Modeling and Analysis** – *the simulation of operational conditions and prediction of the thermal performance of the design through computer models*
  - **Implementation** – *the procurement, assembly, and integration of the necessary thermal hardware for the design*
  - **Testing and Verification** – *exercising of the hardware under test environments similar to operational conditions to verify requirements are satisfied*
  - **Operation** – *the checkout and usage of the thermal product under operating conditions*

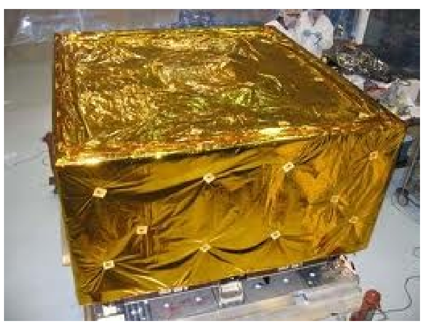
What makes this even more difficult for Space?

- *With no atmosphere, convection/conduction cannot be used to reject heat. Only radiation can reject waste heat…(note radiation is proportional to surface area and Temp^4 in K or R)*
  - Fortunately for heat rejection purposes, space is very cold (~4K).
  - But this cold environment may require heating for some components (which requires power and may affect Solar Array sizes)
  - Radiators for very cold components are challenging, as the effectiveness of radiative heat rejection greatly diminishes with lower temperatures
- *Being on a moving spacecraft means that heat sources in space may be at different locations at different times relative to the spacecraft…makes for a frequently varying environment, especially considering orbital eclipses*
- *Many space applications include very cold components (i.e. detectors) as well as warm components (e.g. electronics). Necessitates multiple thermal control zones…*
- *Mass and volume are key drivers in space applications. This limits the implementation of some solutions that may be acceptable for terrestrial designs*
- *Space is lacking in gravity, but Earth is not. This makes testing space applications difficult on the ground if they rely on zero gravity operation (e.g. heat pipes)*
- *Space is generally not accessible for repairs – better get the design right and verified before launching into orbit!*
  - The necessity to thoroughly test drives cost, and money is a very finite resource…

What do Thermal Engineers do for Space Designs?

In the simplest of terms, thermal engineers keep spacecraft, instruments, and components from getting too hot or too cold while on orbit

- ***Our accepted design philosophy is to ensure that the design meets requirements under stacked worst case conditions (Max/Min power, optical property variations, orbits, etc)***
  - **Predictions are bounding case values, not instantaneous orbital predictions !!!**
  - High number of factors taken into account by thermal from other subsystems
- ***The most basic function is to size radiators and heaters to maintain components within provided limits based on mechanical layout, power, and orbital inputs provided to thermal***
  - A variety of thermal devices are available to accomplish this goal…



Multi Layer Insulation

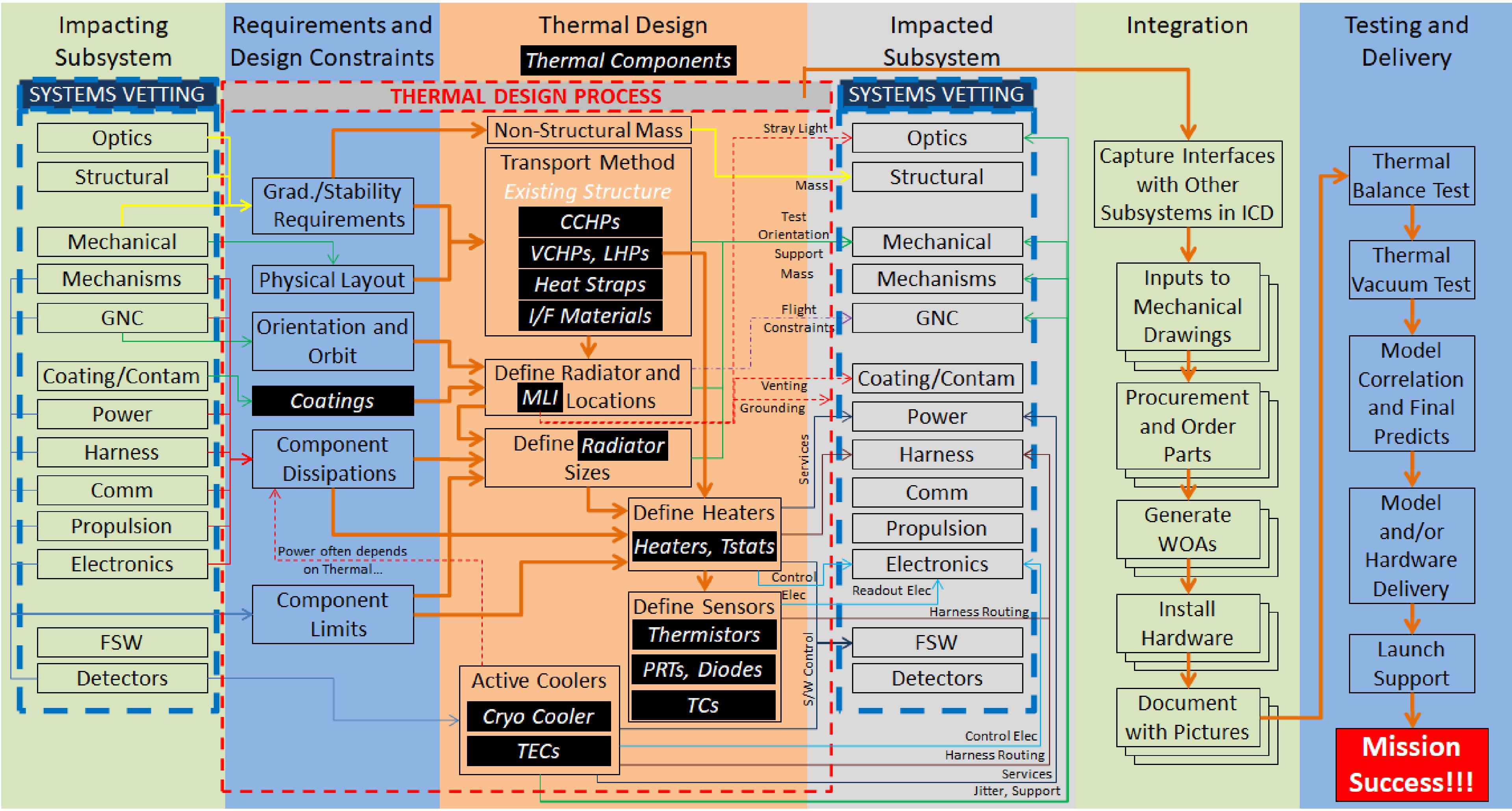
Heater/Thermostats

Radiator

Heat Pipes and Loop Heat Pipes

- ***The Thermal subsystem is strongly coupled with many subsystems on a typical spacecraft***
  - Either we really need inputs from them to do our design…
  - Or we need resources from them…
  - Or we need to constrain what they can do in flight or testing…

Space-Based Thermal Engineering Process



Space Flight Applications

- *Thermal Engineering for Space Flight Applications occurs at many levels of complexity throughout the project life cycle, from early concepts → design maturation → testing of final designs → operations*
  - Board Level
  - Box Level
  - Instrument Level
  - Spacecraft Level
- *Aside from the obvious thermal requirements to meet temperature limits, a number of other implicit and explicit requirements exist:*
  - Minimize Mass, Power, and Volume
  - Fit within Cost and Schedule constraints
  - Consider accessibility (MLI blankets) and moving interfaces
  - Consider Electrostatic Discharge, Shielding, and Contamination concerns
  - Evaluate heat flows across interfaces and ensure they meet ICD requirements

Thermal Design

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Thermal Design Agenda

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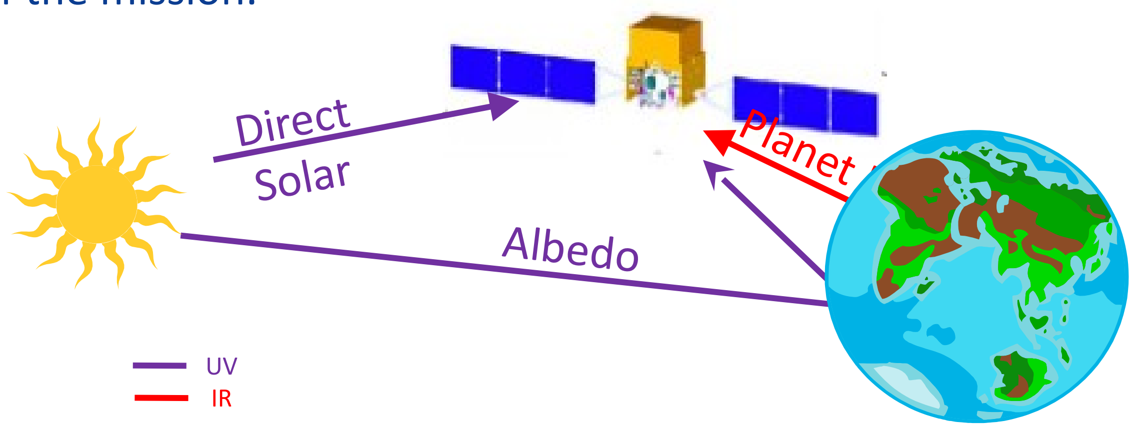
Challenges of Designing for Space

Why is Space Thermal Design a Challenge?

- Satellites experience harsh environments in orbit, ranging from ~393K (full sun near Earth) for part (or all) of an orbit to ~3K in shadow/eclipse. This can cause drastic temperature changes on a satellite, where most critical parts (electronics/ electrical) want to be around ambient temperature range (253K-313K), resulting in cycling from one extreme to another over the life of the mission.



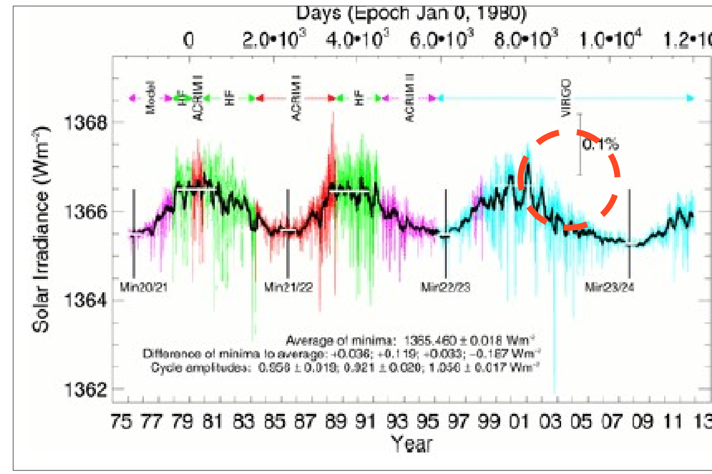
- Science instruments may have challenging temperature requirements ranging from cryogenic (<120K) to ambient, with stability and gradient requirements as well.
- Design must work for all on-orbit conditions as well as for ground operations, launch, ascent, calibration activities, thruster burns, and possibly re-entry.

Thermal Environment(s) of Space

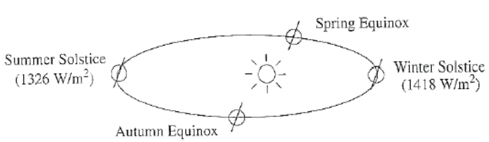
- Space mission must consider external heating sources when developing a thermal design.
- Direct solar heating is the greatest source of heating for most spacecraft
- The solar energy reflected by a planet (albedo) and the outgoing longwave radiation (or Planet infrared energy emitted by a planet/moon/asteroid based on its temperature) is also considered when close enough to the planet or body.
- For heliocentric orbits (i.e., orbits about the sun) that are sufficiently far from a planet or moon, albedo/Planet IR may be negligible:
  - *Geosynchronous orbit (unless cryogenic radiator)*
  - *Interplanetary Cruise phase*
- Cold space itself (not to be neglected) is the cooling effect of deep space, with a background temperature around 4K
- Free Molecular Heating (FMH):
  - Typically encountered only during the launch phase, after fairing separation where sufficient atmosphere remains to cause heating due to high velocity impingement of the particles.
  - While this is usually specified in the applicable launch vehicle user manual, included in an integrated analysis done by the launch vehicle provider, the thermal engineer must be aware of this type of heating to ensure the analysis accurately includes its effect.
- Aeroheating: heating of a solid body produced by its high-speed passage through air (or by the passage of air past a static body), whereby its kinetic energy is converted to heat by adiabatic heating.
  - Not typically done by GSFC (ARC, LaRC)

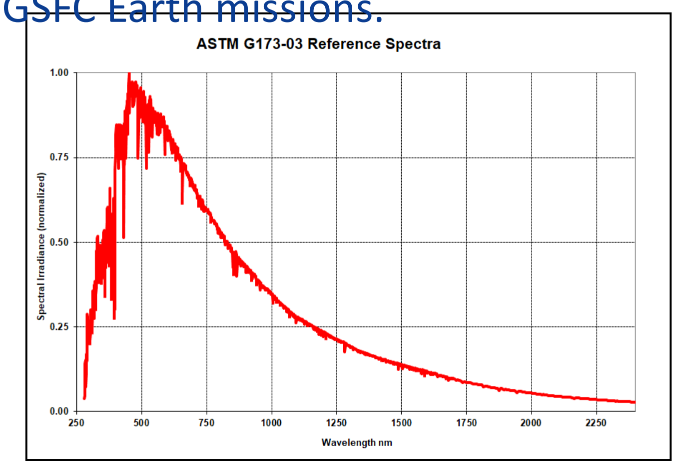
Environment – Solar Irradiance

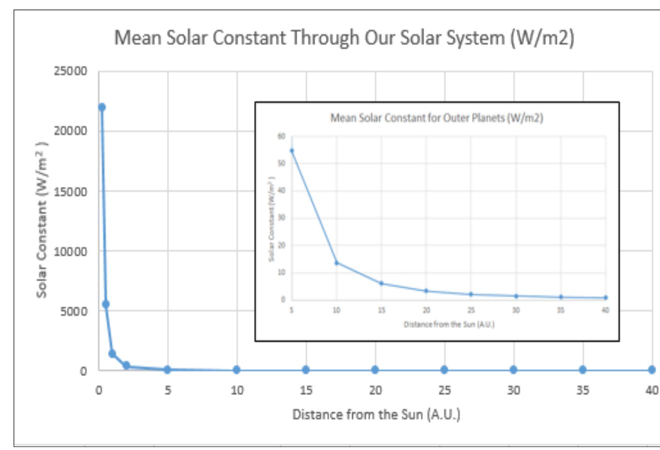
- Solar irradiance is the primary heating source to be considered in thermal design for most satellites. The intensity varies with distance from the sun; inversely proportional to the square of the distance from the sun (energy from an expanding sphere).



- Based on a series of measurements since 1969 that document the recognized mean (top of the atmosphere, or 30km above the Earth's surface) solar irradiance value of 1367 W/m2. This value is then adjusted for the 1.67% eccentricity of the Earth's orbit about the sun and for an accepted 0.4% measurement error, to arrive at a range of solar constant to be used as a reference for determining the solar constant for GSFC Earth missions.
  - **Min: 1316 W/m²**
  - **Mean: 1367 W/m²**
  - **Max: 1420 W/m²**







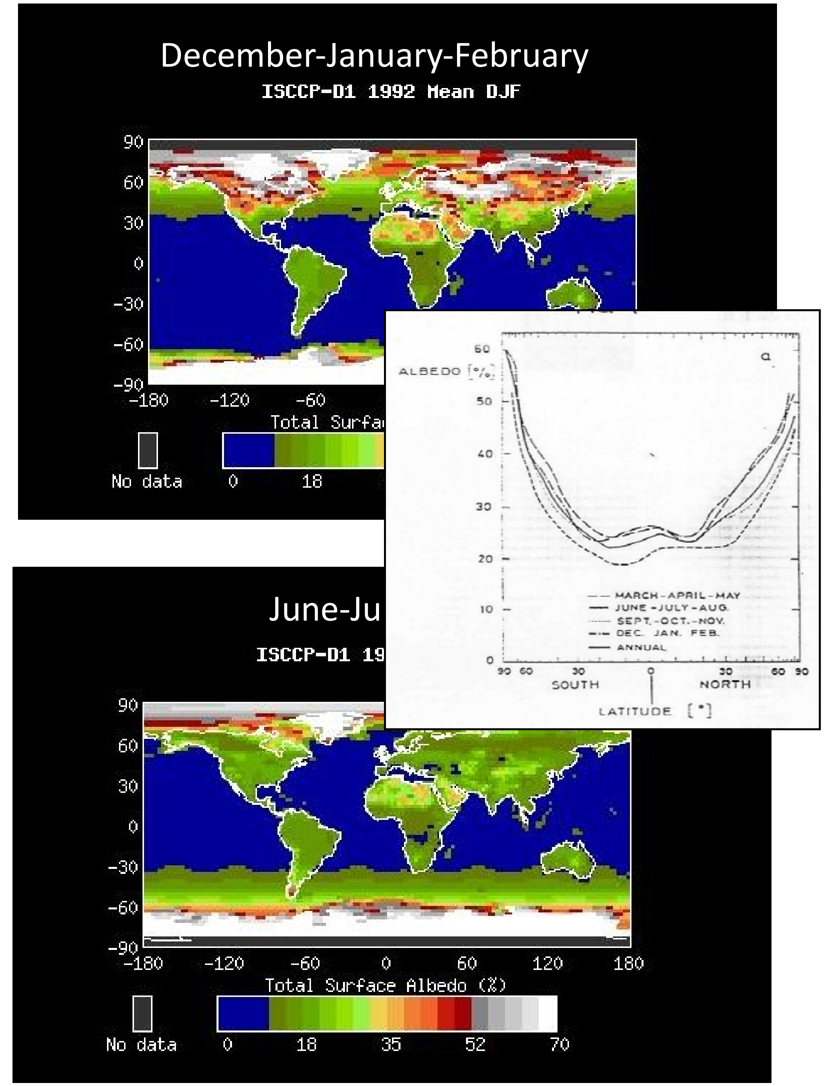
Environment – Albedo

- Albedo is sunlight reflected off a planet or moon. This is usually expressed as the fraction of incident sunlight that is reflected back to space and is highly variable.
  - *A first approximation is that this reflection or "scattering" is Lambertian, or equal in all directions. The typical range of albedo values prescribed are:*

0.25 < ALB < 0.35 (orbit average)

- Since this reflection actually is dependent on the solar zenith angle, it can vary significantly with latitude in the sunlit portion of the orbit and the view factor of the satellite surface to the reflecting planet surface.
  - *Reflectivity is greater over land as compared with oceans and generally increases with decreasing local solar-elevation angles and increasing cloud coverage.*
  - *Because of greater snow and ice coverage, decreasing solar elevation angle, and increasing cloud coverage, albedo also tends to increase with latitude.*
- Another consideration is the thermal time constant of the various surfaces that receive albedo energy. A probabilistic assessment of these variations can be used if the thermal time constant of the system warrants it.

See: Spacecraft Thermal Control Handbook, David Gilmore, et al, Aerospace CorpVol 1, Chapter 2



Environment – Planetary IR
(aka OLR: Outgoing Longwave Radiation)

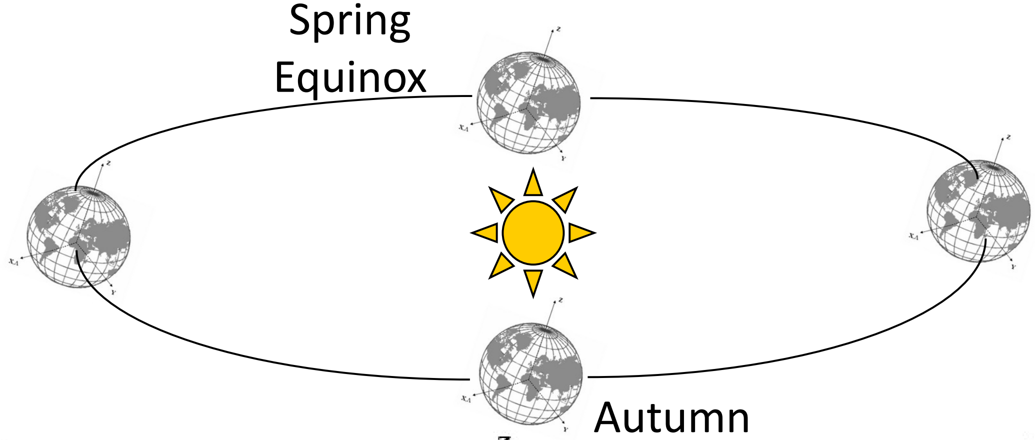
- Sunlight incident on the Earth (that is not reflected as albedo) is absorbed and eventually re-emitted as IR energy or blackbody radiation.
  - *The typical range prescribed for near-Earth missions is:*
    208 < OLR < 265 W/m² [243K < T_{BB} < 258K]
  - *But, Earth IR (EIR) should be calculated using the energy balance equation*: EIR = (1 – ALB) x SOL/4.0A
    214 < EIR < 266 W/m² [214K < T_{BB} < 266K]
- This IR heating is a combination of energy emitted from the planet/body surface being orbited, and any atmospheric gases/cloud cover that may be present.
  - *While local variations may be less severe than localized albedo variations, the IR spectral emission bands can be more complex. A probabilistic assessment of these variations can also be used if the thermal time constant of the system warrants it.*
- Noting that Diurnal variations for bodies like the Moon (85°K to 400°K) or Mars (138°K to 293°K) are much more significant. Values for other planets, moons, etc should be determined from available data and concurred with by the Thermal Branch.

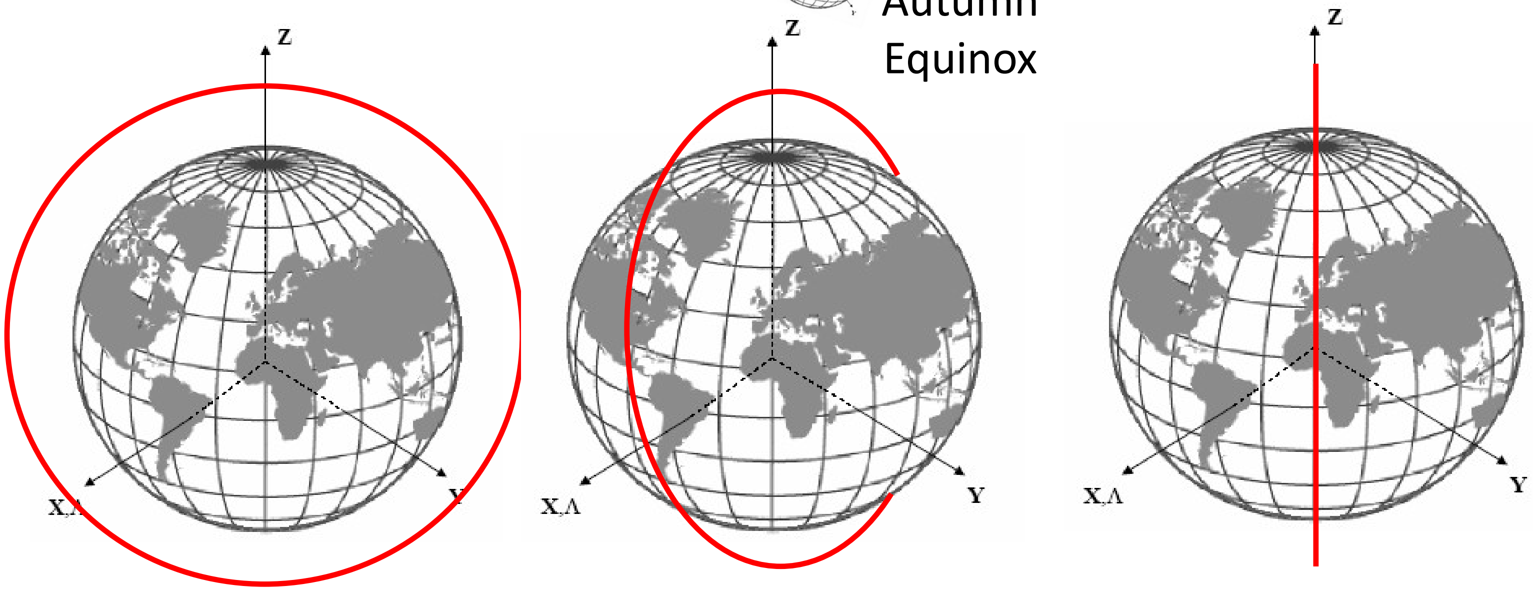
Orbit Mechanics - Sun (β) Angles and Spacecraft Orientation

- GSFC missions have expanded tremendously from the initial Low Earth Orbits of the earth observation missions to geosynchronous, lunar, interplanetary, etc. Since the solar irradiance was just shown to likely be the singular most important external heating contribution for most satellite missions, knowing the orientation with respect to the sun is key.
  - *Beta (β) angle is defined as the minimum angle between the solar vector and the orbit plane, and is function of the nodal crossing, altitude and orbit inclination and can vary from -90° < β < +90°. Some missions are designed to be "sun-synchronous" with a more restricted beta angle range.*
- As important as β angle, is the spacecraft orientation
  - *Many non-LEO/GEO missions (such as Lagrange 1/Lagrange 2, Lunar, Mars, interplanetary, etc) may also include multiple mid-course corrections, which are typically longer thruster burns where the orientation of the spacecraft is driven by the thrust direction*
  - *Furthermore, some more recent missions employ Solar Electric Propulsion, which often has long thrusting periods (with much smaller thrusts) where spacecraft pointing is dictated by thrusting needs and not thermal needs*
- An Excel spreadsheet-based beta angle calculator has been developed for use at GSFC by Dave Everett. The most recent version may be found on the ETD/545 WIKI. A similar capability is also included in the ThermalTextbook_v2.xls on the ETD/WIKI
- Furthermore, a presentation on Orbital Mechanics for Thermal Engineers by Matt Garrison is also available on the ETD/545 Wiki (Thermal Engineering Mini Courses-Subsystem Courses)

Recommend that sun angles for interplanetary cruise be determined and provided by GNC (heliocentric trajectories).

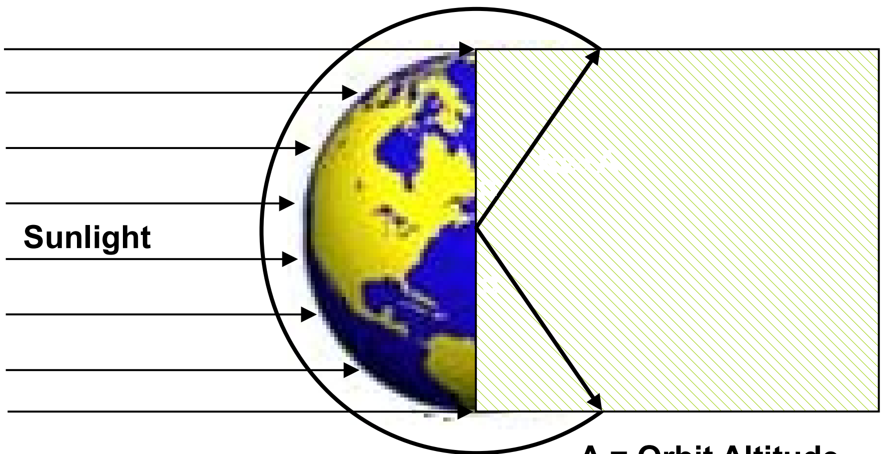
Beta Angle





$\beta = 90°$ $0° < \beta < 90°$ $\beta = 0°$

Eclipses



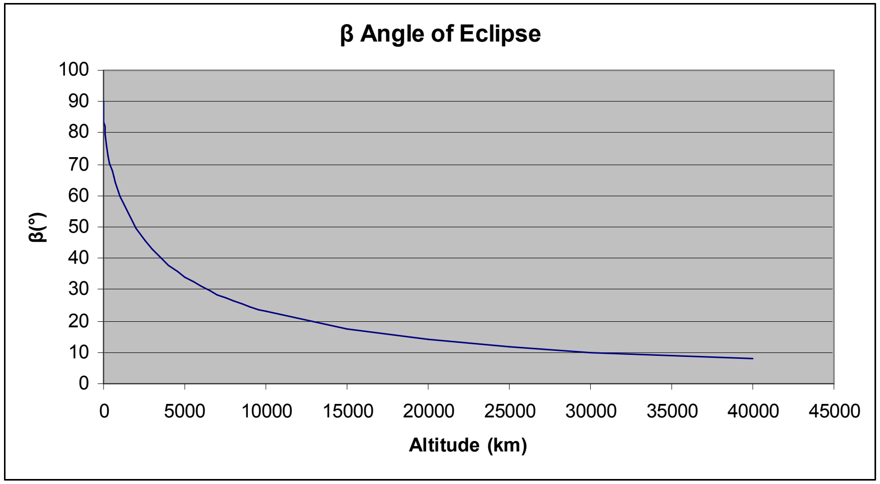
A = Orbit Altitude
Re = radius of the Earth

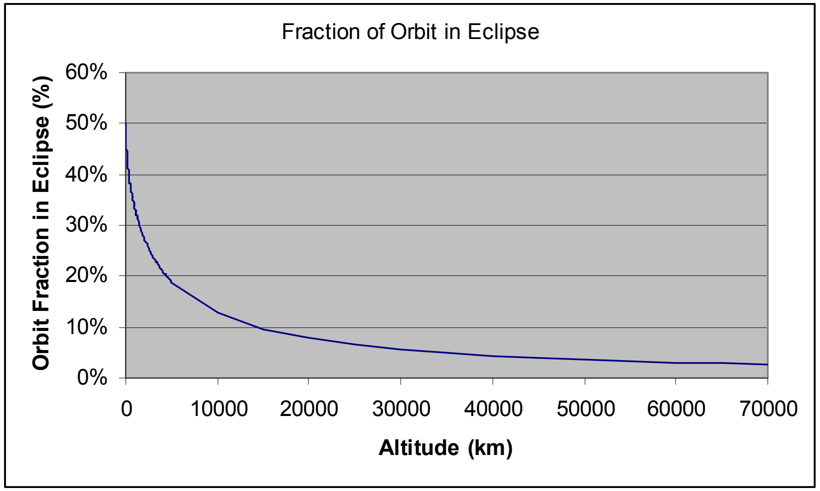
- During eclipses, both the solar loading and albedo drop to zero as the planet or body blocks the view to the sun. Therefore, during eclipse, Planet IR is the only environmental heat source

$$\alpha = \cos^{-1}\left(\frac{R_E}{R_E + A}\right)$$

$$\text{Fraction of time in sunlight} = \frac{180 + 2\alpha}{360}$$

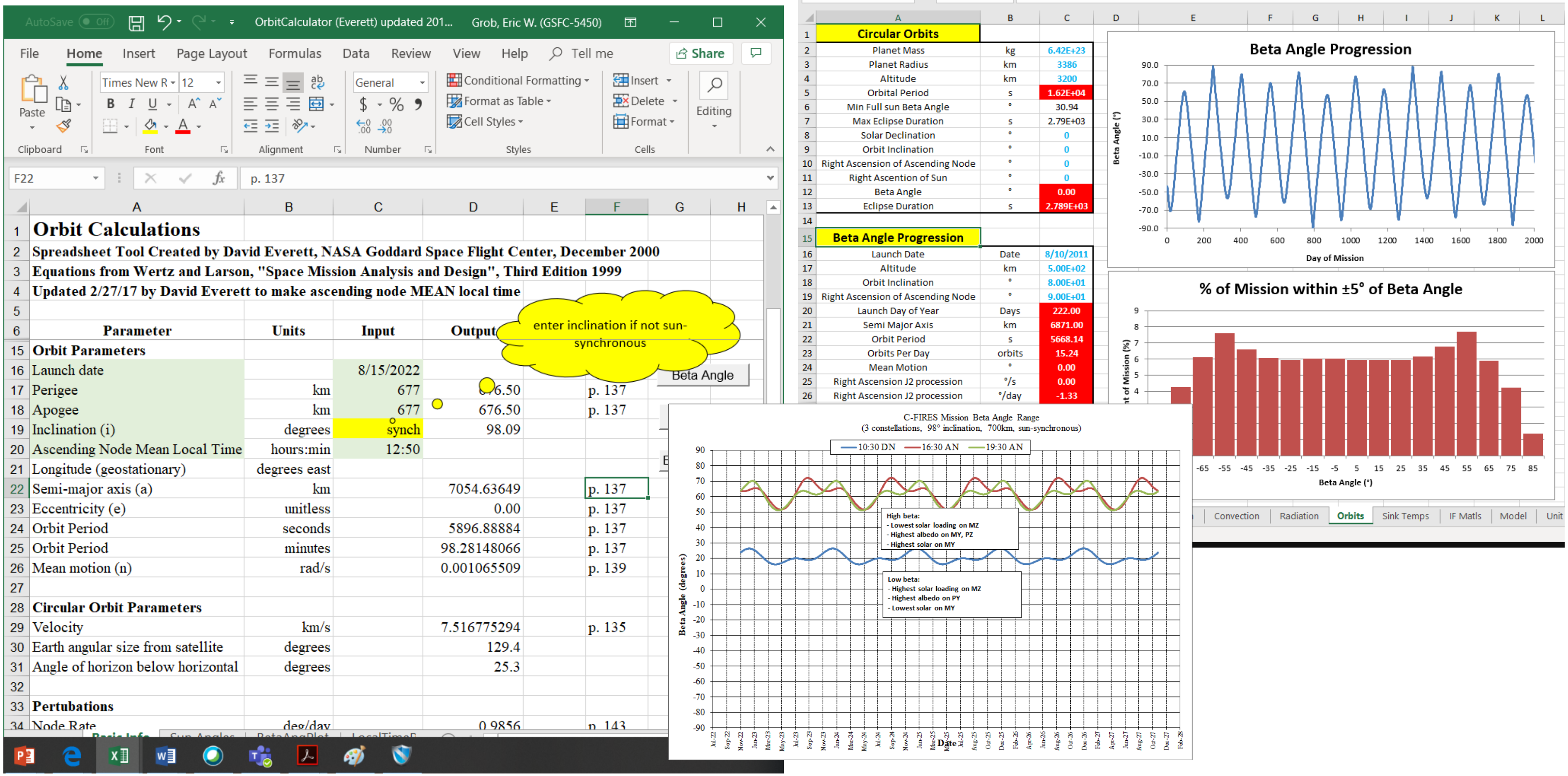
$$\text{Fraction of time in eclipse} = \frac{180 - 2\alpha}{360}$$





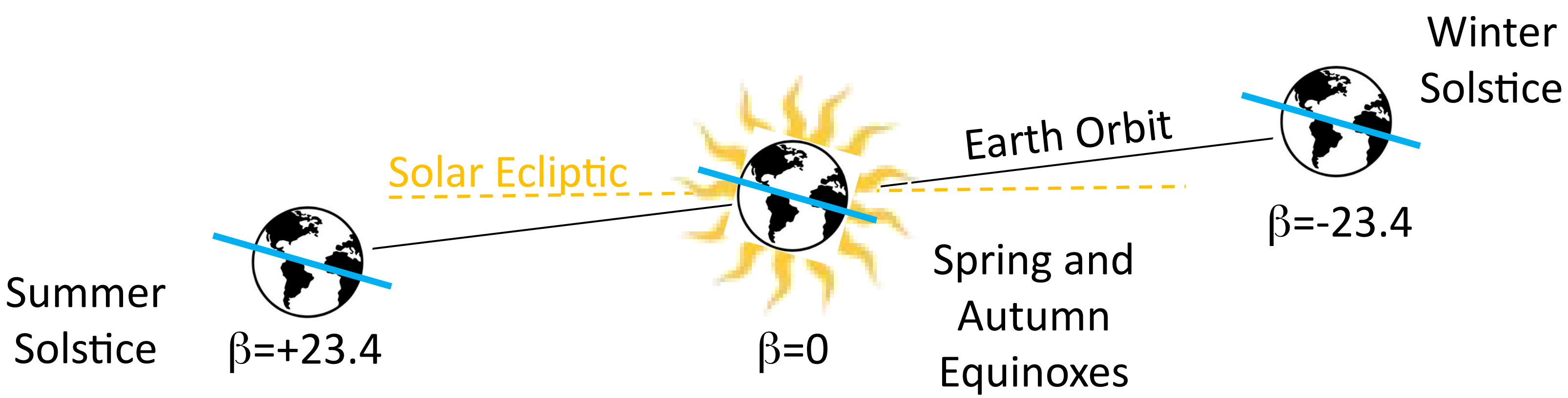
Beta Angle & Eclipse Calculators

- Created by Dave Everett, can be found on our wiki
- Based on Inputs from Matt Garrison



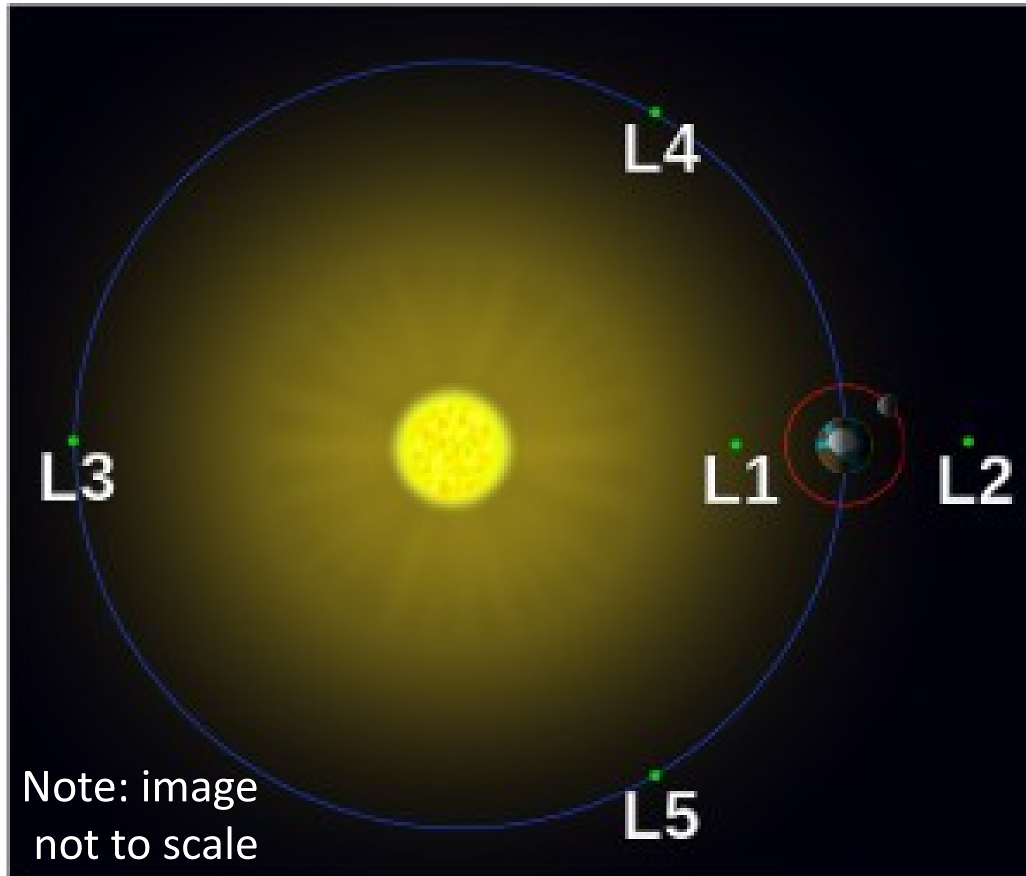
Geostationary Orbit

- Many missions orbit in a Geostationary orbit, where the period is exactly equal to one Earth day and the orbit is in the equatorial plane.
- These orbits have the advantage of observing the same ground location at all times as the satellite rotates with the Earth to remain fixed above the ground, relatively speaking
- Due to the tilt of the Earth's rotational axis relative to the normal to its orbit plane, the range of Beta Angles for Geostationary orbits is -23.4° to +23.4°
- In general, the only consequential environmental source for Geostationary orbits is Solar. Albedo and Planet IR are usually negligible



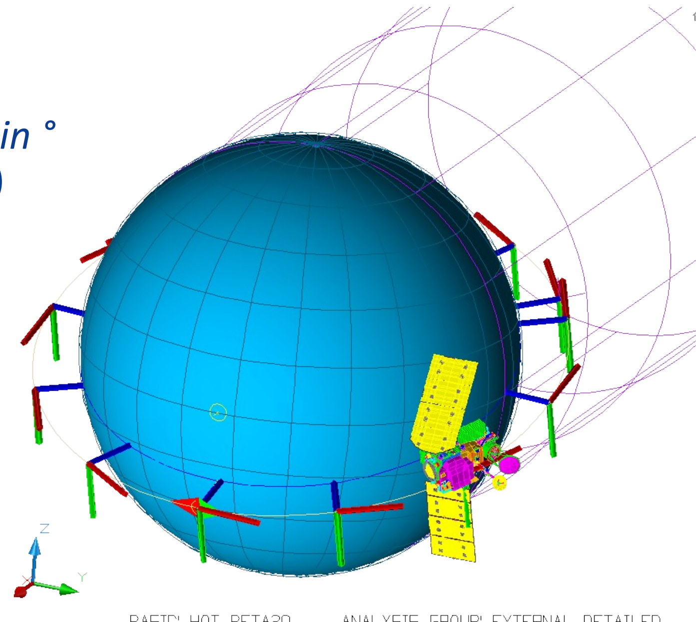
Lagrange Points

- Lagrange points are special locations in the solar system where the gravitational and body forces balance. These points are desirable for spacecraft since they require considerably less fuel to maintain their position
- Besides being optimum for fuel usage, the Lagrange points are also good thermal points as they present very stable and consistent environments
- L1 is at about 0.99 AU. Note that spacecraft here will see full sun
- L2 is at about 1.01 AU. Spacecraft here need to orbit outside of the shadow cone of Earth to allow for illumination of the Solar Arrays
- Lagrange points also can generally neglect albedo and Earth IR environmental sources



How are these Heating Sources Determined?

- **Thermal software allows for the specification of orbital parameters (Beta Angle, Altitude, Spacecraft Orientation, Number of Orbit Positions, etc), that when combined with a Geometric Thermal Model can compute the absorbed heat loads from celestial sources**
- **Other sources that are sometimes included are:**
  - *Free Molecular Heating: a near vacuum environment where stray molecules of gas may travel large distances before colliding and releasing kinetic energy*
  - *Solar Wind: solar particle ejections that may release kinetic energy when colliding with surfaces*
  - *Forced Convection (e.g. Fairing Air Conditioning): forced air flow by an air conditioning unit to cool a spacecraft while encapsulating in the fairing of the launch vehicle*
  - *Natural Convection: circulation of air driven by buoyancy forces*
- ***Some other terms used when representing orbits:***
  - *Anomaly: the relative location of a vehicle in the orbit, expressed in °*
  - *Nadir: in the direction of the body being orbited (usually a planet)*
  - *Zenith: away from the direction of the body being orbited*
  - *Eclipse: when the orbited object blocks the view of the orbiting object from the sun (Solar+Albedo=0)*
  - *Terminators: points just before entering and exiting eclipse*
  - *Orbit Noon or Subsolar Point: when the angle between zenith and the solar vector is at a minimum (usually 0° anom.)*
  - *Orbit Midnight: when the angle between zenith and the solar vector is at a maximum (usually 180° anom.)*



Constraints and Verification of Space Designs

- Space applications are challenging given constraints on mass, volume, and power that may not be considered in thermal designs for other fields…
  - *With a significant part of the cost of a mission driven by a launch vehicle, mass is a very important constraint in space design, as the satellite mass cannot exceed the launch capability of the rocket*
  - *Also implied in the selection of a particular launch vehicle is volume, given finite sizes of the fairing atop a rocket which contains the spacecraft*
  - *Power is also an important factor, as it directly drives the size and accommodation of a solar array for a spacecraft*
- Verification of space flight designs may also present challenges…
  - *The testing of a flight design needs to provide similar conditions as flight, including vacuum, cold space view simulators, and radiative environmental heating simulation*
  - *The usage of devices whose performance relies on a micro-gravity environment can also be a driver in the thermal design of spacecraft, particularly for two-phase heat transport devices*
  - *Lastly, the importance of testing to discover any workmanship or design flaws cannot be overstated. Options to fix a problem after launch are nearly non-existent…*

Heat Transfer Basics Review

Thermodynamics

- *Thermodynamics is the branch of physics that deals with temperature, heat, and work their relation to energy, entropy, and the physical properties of matter*
- Thermodynamics generally has four governing laws
  - The zeroth law of thermodynamics defines thermal equilibrium and forms a basis for the definition of temperature: If two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.
  - The first law of thermodynamics states that, when energy passes into or out of a system (as work, heat, or matter), the system's internal energy changes in accordance with the law of conservation of energy.
  - The second law of thermodynamics states that in a natural thermodynamic process, the sum of the entropies of the interacting thermodynamic systems never decreases. A common corollary of the statement is that heat does not spontaneously pass from a colder body to a warmer body.
  - The third law of thermodynamics states that a system's entropy approaches a constant value as the temperature approaches absolute zero. With the exception of non-crystalline solids (glasses), the entropy of a system at absolute zero is typically close to zero.

- From Wikipedia

Heat Transfer

- *Heat transfer is a discipline of thermal engineering concerned with the generation, use, conversion, and exchange of thermal energy (heat) between physical systems.* - From Wikipedia
- The most common modes of heat transfer are:
  - Conduction: the transfer of energy related to the vibration of molecules as a function of temperature
  - Convection: the transfer of energy related to a moving fluid across a surface
  - Radiation: the transfer of energy related to electromagnetic radiation generated by the thermal motion of particles in matter
- One other matter to consider is the storage or release of energy as f(T)
- All three of

Fried eggs are heated by conduction from the pan

Blowing across a hot cup of coffee cools it by convection

Curly fries (and other fast "food") are heated by radiation from a lamp

Conductive Heat Transfer

One-Dimensional Conductive heat transfer through a material is estimated as:

$$Q(T) = k(T) * A_x * \Delta T / L$$

where:

- Q(T) - heat flow (function of temperature)
- k(T) - conductivity of material (function of temperature)
- A - cross-sectional area
- L - distance between two locations
- ΔT – Temperature difference between two locations

Note: For many spacecraft applications the conductivity may be considered constant since it is essentially a room temperature system. Temperature dependence is necessary for low temperature modeling or when the temperature range varies drastically during the mission.

Basics - Conduction Heat Transfer

- All materials are conductive, but some have much better conductivity than others
  - Metals vs. Non-metals
  - Alloy differences can also affect thermal conductivity
- The properties typically used for thermal analysis are: Density, ρ; Thermal Conductivity, k; Specific Heat, C_p
- Low conductivity materials used as isolators, while higher conductivity materials may be used as spreaders or heat straps

Solid Material Thermal Properties

Material	ρ (kg/cm³)	k (W/cm°C)	c_p (W-hr/kg°C)
Aluminum			
208	0.00277	1.212	
222	0.00277	1.333	
242	0.00277	1.506	
295	0.00277	1.437	
B295.0	0.00277	1.610	
308	0.00277	1.419	
319	0.00277	1.142	
355	0.00277	1.506	
C355.0	0.00277	1.419	
356	0.00277	1.593	
A356.	0.00277	1.593	
A380.	0.00277	1.004	
A413.0	0.00277	1.212	
443	0.00277	1.454	

Source: Spacecraft Thermal Control Handbook, Vol I, Appendix B

Material	Thermal conductivity (W/m K)*
Diamond	1000
Silver	406
Copper	385
Gold	314
Brass	109
Aluminum	205
Iron	79.5
Steel	50.2
Lead	34.7
Mercury	8.3
Ice	1.6
Glass,ordinary	0.8
Concrete	0.8
Water at 20° C	0.6
Asbestos	0.08
Fiberglass	0.04
Brick,insulating	0.15
Brick, red	0.6
Cork board	0.04
Wool felt	0.04
Rock wool	0.04
Polystyrene (styrofoam)	0.033
Polyurethane	0.02
Wood	0.12-0.04
Air at 0° C	0.024
Helium (20°C)	0.138
Hydrogen(20°C)	0.172
Nitrogen(20°C)	0.0234
Oxygen(20°C)	0.0238
Silica aerogel	0.003

Convective Heat Transfer

Convection heat transfer is described by the following equation:

$$Q(T) = A * h(T) * (T_s - T_f)$$

where:

- $Q(T)$ - heat flow from position 1 to position 2
- A - Surface area
- $h(T)$ - convection coefficient or heat transfer coefficient
- T_s - temperature of surface
- T_f - temperature of fluid (aka Freestream Temperature)

There are two main types of convection: free and forced

For Free Convection, the motion is driven by buoyancy forces/gravity

For Forced Convection, the motion is driven by an external fan or pump or the motion of the article in a fluid medium (e.g. aircraft)

The value for h is generally a complex derivation that depends on geometry, fluid properties, velocity (forced) or buoyancy (free), flow type (laminar vs turbulent), etc

Note: For spacecraft applications, convection does not apply with some exceptions: re-entry/launch aeroheating, ground operations in ambient conditions, pumped fluid loops, lower altitude balloons (which are not quite the vacuum of space)

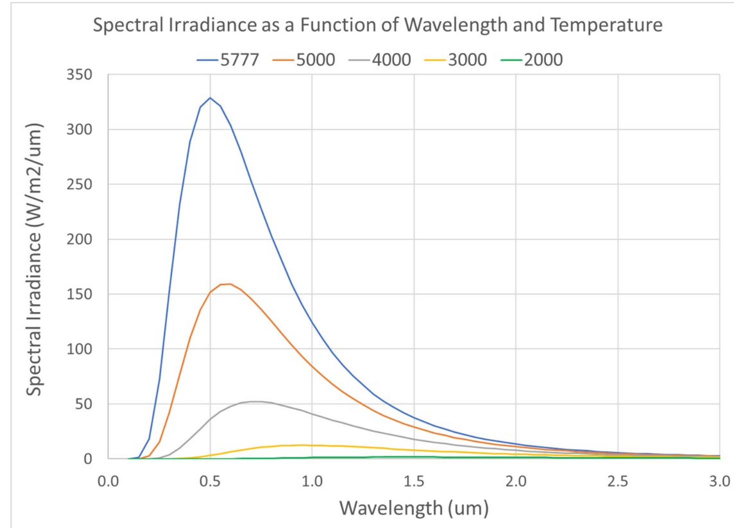
Thermal Radiation

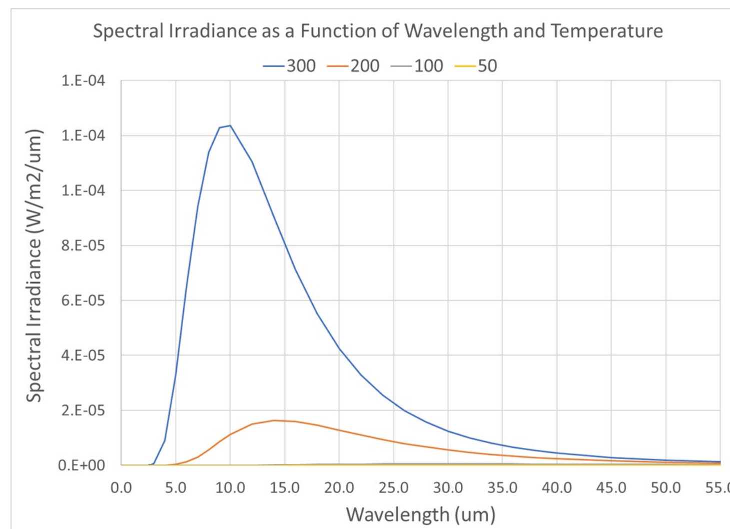
- Thermal Radiation is perhaps the most complex mode of heat transfer, being electromagnetic radiation that is emitted solely based on <u>temperature</u> and requiring no intermediary medium.
- It is governed by Planck's Law, which computes the Spectral Irradiance as a function of Temperature and Wavelength

$$B(\lambda,T) = 2hc^2/\lambda^5 / [\exp(hc/\lambda kT) - 1] * 1E6 \text{ um/m}$$

(Multiply further by 4π steradian to get W/m2 um)

- Where:
  - B Spectral Irradiance ($W/m^2/str/um$)
  - λ Wavelength in um
  - h Planck's Constant: 6.62607015E-34 J/Hz
  - c Speed of Light in Vacuum: 3.0E8 m/s
  - k Boltzman Constant: 1.380649E-23 J/K
  - T Temperature in K





Thermal Radiation - Blackbody

- Planck's Law can be further manipulated, integrating over all wavelengths, 0 to $\pi/2$ and 0 to 2π for a hemisphere and boils down to the Stefan-Boltzman Law, which states:

$$P = \sigma T^4$$

- Where:
  - P Total power emitted from a body per unit area
  - σ Stefan-Boltzmann constant: 5.67x10-8W/(m^2K^4)
  - T temperature of blackbody surface (K)
- Considering Q = P * A, the familiar $Q=\sigma AT^4$ falls out for the heat emitted by a blackbody as a function of temperature
- A blackbody surface is an idealized concept where the surface is a perfect absorber and emitter of thermal energy.
- Taking the Sun's temperature as 5777 K, the Stefan-Boltzman law can be used to estimate the flux at Earth. Given the Sun's radius of 696349 km and the distance of the Earth from the sun of 1.496E8 km, the flux at the solar surface can be estimated as 5.67E-8* (5777^4) * $4\pi(696349E3)^2$. However, by the time that flux through a given angular section reaches 1 AU, it has spread out over $4\pi(1.5E11)^2$
  - So, taking 5.67E-8 * (5777^4) * $696349^2/1.496E8^2$ yields 1368 W/m^2

Radiation View Factors and Reciprocity

So far, the discussion around radiation has focused only on emitted energy, but not on energy exchanged (or transferred between two bodies). To address this, the concept of a View Factor is introduced which represents the percentage of the total field of view of Surface 1 occupied by Surface 2.

$$Q_{12} = \sigma\ A_1 F_{12} (T_1^4 - T_2^4)$$

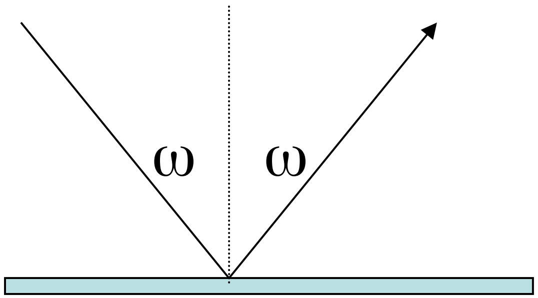
Where:

- Q_{12} - heat flow from surface 1 to surface 2
- σ - Stefan-Boltzman constant: $5.669E^{-12}$ $W/cm^2 K^4$ or $0.1714E^{-08}$ $Btu/hr\ ft^2 R^4$
- A_1 - surface area associated with surface 1
- F_{12} - geometric view factor from surface 1 to surface 2
- T_1 - temperature of surface 1 (in Absolute units K [C+273.15] or R [F+459.67])
- T_2 - temperature of surface 2 (in Absolute units K [C+273.15] or R [F+459.67])

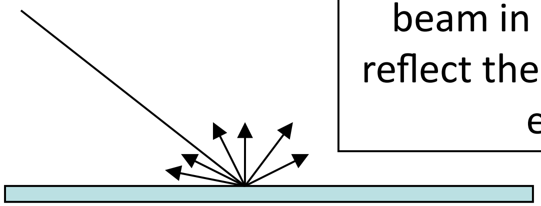
View Factors also follow a reciprocity rule where $A_1F_{12} = A_2F_{21}$. This can be derived considering the heat absorbed by Surface 2 from Surface 1 as $Q_2 = \sigma\ A_2 F_{21} (T_1^4)$. Likewise, the heat absorbed by Surface 1 from 2 is $Q_1 = \sigma\ A_1 F_{12} (T_2^4)$. When the surfaces are at equal temperatures in equilibrium, the *net* energy exchange is zero (Heat from 1 to 2 [Q_2] equals Heat from 2 to 1 [Q_1]). Therefore $A_1F_{12} = A_2F_{21}$

Radiation – A bit More Complexity

- Everything discussed up to now has been in terms of a black body. But no real surfaces are truly a black body…
- Furthermore, if no surfaces are perfect emitters, then likewise no surfaces can be perfect absorbers
- Energy emitted by Surface 1 and incident on Surface 2 will act in 1 of 3 ways:
  - It will be absorbed (α)
  - It will be transmitted (τ)
  - It will be reflected (ρ)
  - This necessitates that $\alpha + \tau + \rho = 1.0$
- Energy reflected (or transmitted) may be done so either diffusely (scattered in all directions) or specularly (where the incidence angle = the reflective angle)



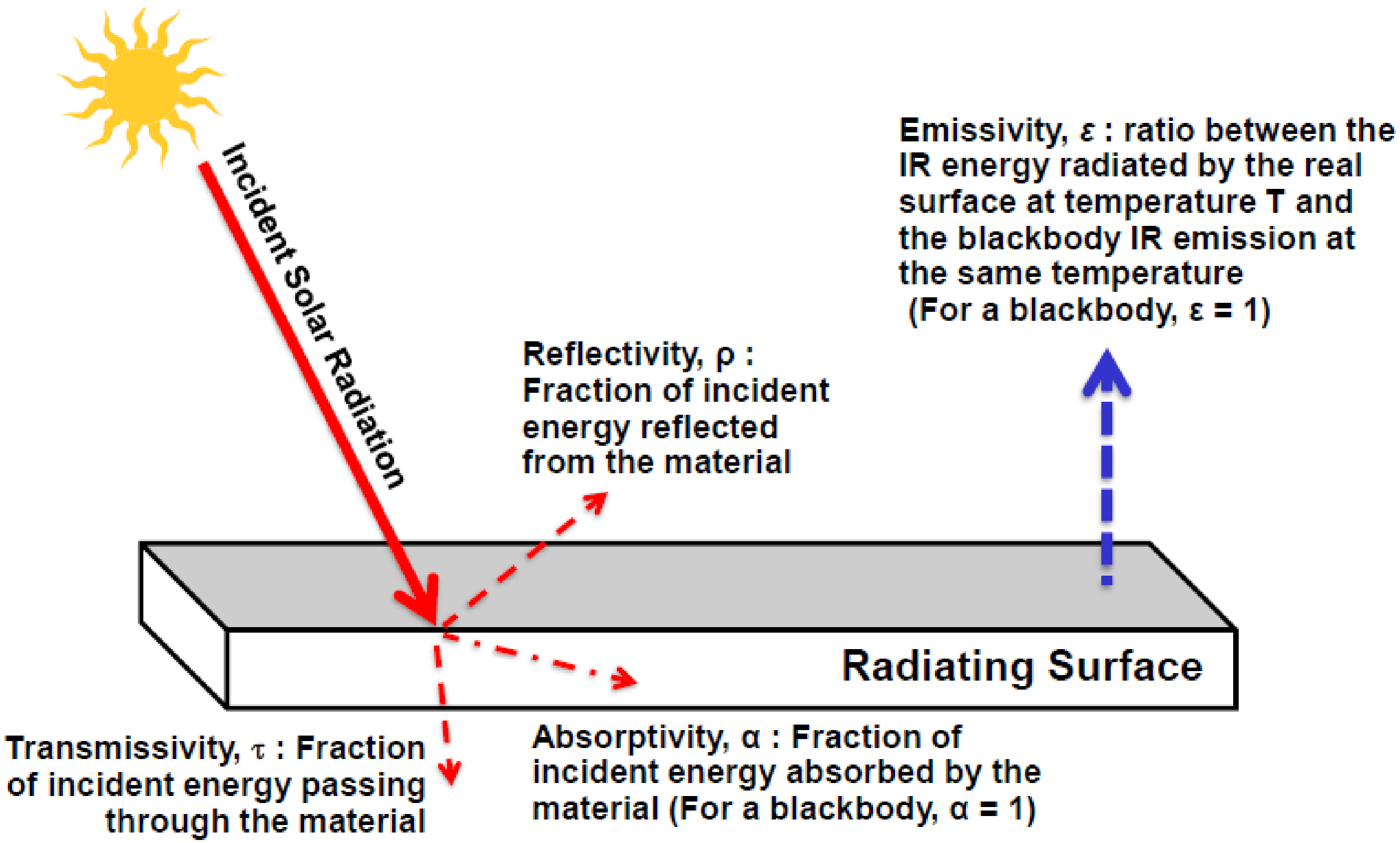
Specular Reflection



Diffuse Reflection

A diffuse surface is one that distributes an incident beam in all directions; A specular surface would reflect the beam such that the angle of incidence is equal to the angle of reflection.

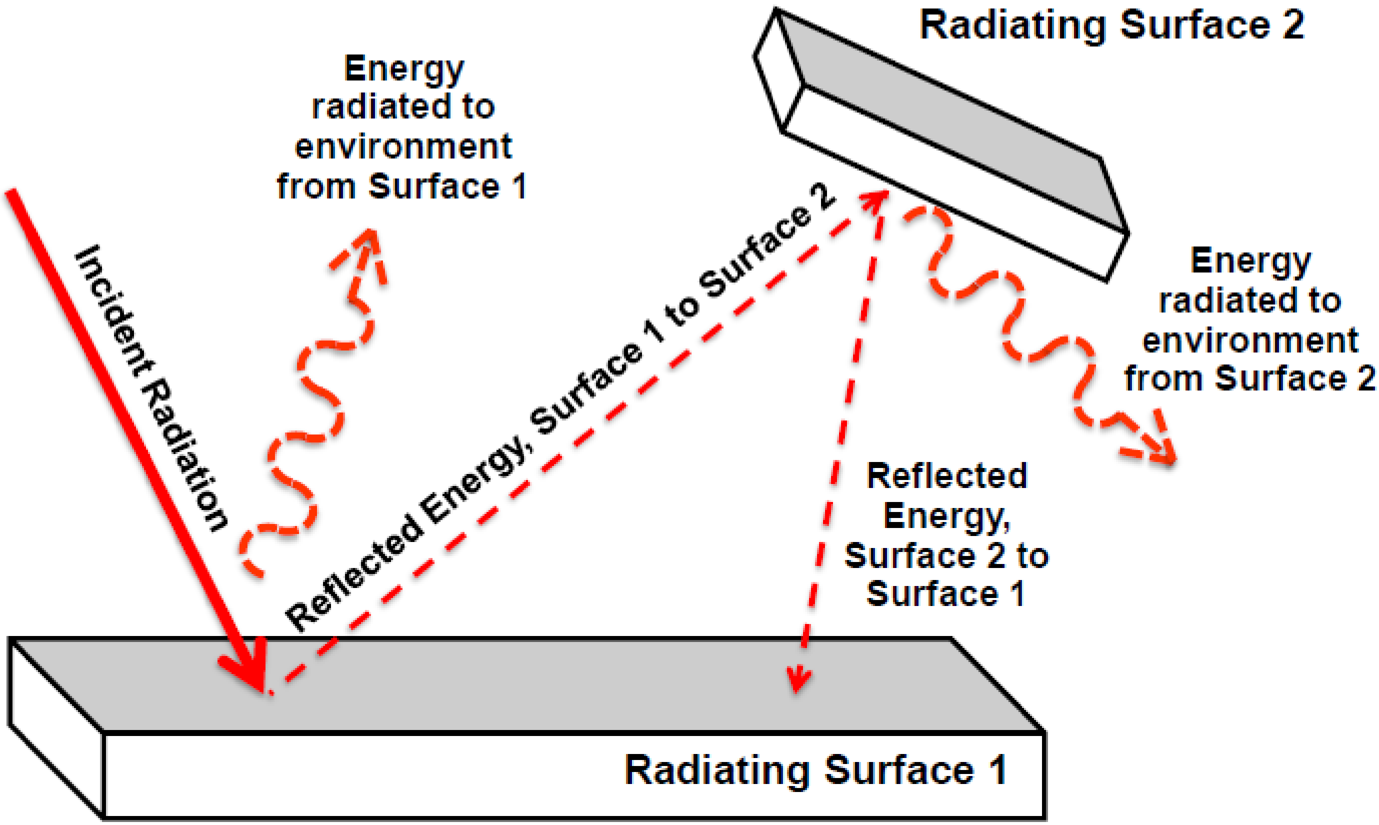
Real Bodies



For a given surface: $\alpha + \rho + \tau = 1$

Multiple Real Bodies

- Now what about radiation between two or more surfaces?



- To determine the energy exchange in this system, we must first know the optical properties of the surfaces, and their views to each other

Radiation Heat Transfer – Gray Body

So, if a surface is not a perfect absorber or emitter, then a new term called emissivity (ε) needs to be introduced. ε represents the fraction of energy emitted by a surface based on its thermo-optical properties compared to a blackbody (where $\varepsilon = 1$).

$$\mathbf{Q_{12} = \sigma \underbrace{\varepsilon_1 A_1 B_{12}}_{\varepsilon_i A_i B_{ij} \text{ often referred to as a Radk or GR}} (T_1^4 - T_2^4)}$$

Where:

- Q_{12} - heat flow from surface 1 to surface 2
- σ - Stefan-Boltzman constant: 5.669E^{-12} W/cm^2 K^4 or 0.1714E^{-08} Btu/hr ft^2 R^4
- A_1 - surface area associated with surface 1
- ε_1 - emissivity of surface 1
- B_{12} - interchange factor from surface 1 to surface 2 (aka Script F)
- T_1 - temperature of surface 1 (in Absolute units K [C+273.15] or R [F+459.67])
- T_2 - temperature of surface 2 (in Absolute units K [C+273.15] or R [F+459.67])

The geometric view factor is now replaced with an interchange factor (also called a Script F), which accounts for the Gray body nature of the surfaces in the Field of View

Radiation Heat Transfer – Gray Body

Consider a perfect cube, with the bottom having an ε of 0.9, the sides having an ε of 0.1 and the top being open to deep space. The view factor from any one side to any other in a cube has a closed form solution of 0.2.

Start with 0.9*0.2 to Node 2 from Node 1 = 0.18

Of the 0.18, 0.1 gets absorbed by node 2, 0.162 gets reflected from 2

Of the 0.162 that gets reflected:

0.162*0.2*1 goes to space

0.162*0.2*0.9 gets absorbed by 1, 0.162*0.2*0.1 is reflected by 1 …

0.162*0.2*0.1 gets absorbed by 3, 0.162*0.2*0.9 is reflected by 3 …

0.162*0.2*0.1 gets absorbed by 4, 0.162*0.2*0.9 is reflected by 4 …

0.162*0.2*0.1 gets absorbed by 5, 0.162*0.2*0.9 is reflected by 5 …

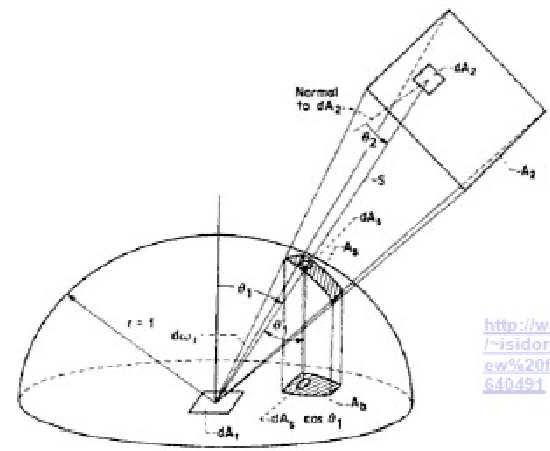
As can be seen, the book-keeping to handle reflected energy to generate the interchange factor quickly becomes unwieldy without computer aid…

Determining the View/Interchange Factor

- The radiation interchange between surfaces is determined by the geometry of the surfaces, their orientation with respect to each other, and their thermo-optical properties
  - View factors between these surfaces must be determined (this is needed in both heat transfer and applied optics)
  - Although some materials have directional or spectral properties of reflection, some approaches only handle diffuse surfaces
  - A diffuse configuration factor is the fraction of uniform diffuse energy leaving a surface that reaches another surface
- There are several methods for calculating view/interchange factors:
  - Nusselt unit sphere
  - Hemicube
  - Direct integration
  - Monte Carlo Ray Tracing (Discussed in the Thermal Analysis Section)
- Hand calculations may be suitable for simple geometries, but more complex interactions often require computer algorithms

Computing View Factors

- For those that love doing integrals, the formulas for radiation view factors for some simple geometries can be derived.
- Some of these calculations have been tabulated in several references on heat transfer (e.g. Holman, 1986) or the NACA handbook. They range from ~zero (e.g. two small bodies spaced very far apart) to 1 (e.g. one body is enclosed by the other)
- These calculations are possible for simple geometries, but the typical satellite has many surfaces that interact “radiatively”
- Thermal software platforms are used to generate radiation views to space and between the many satellite surfaces. A typical satellite geometry model has 5000-20000 surfaces with calculated radiation view factors numbering in the 100s of thousands into the millions



http://webserver.dmt.upm.es/~isidoro/tc3/Radiation%20View%20factors.htm#_Toc271640491

Related Fact

View factors for slightly more intricate geometries and orientations can become complex very quickly: shown below is the view factor from a rectangle to another rectangle in a parallel plane

$$F_{1-2} = \frac{1}{(x_2 - x_1)(y_2 - y_1)} \sum_{l=1}^{2}\sum_{k=1}^{2}\sum_{j=1}^{2}\sum_{i=1}^{2} (-1)^{(i+j+k+l)} G(x_i, y_j, \eta_k, \xi_l)$$

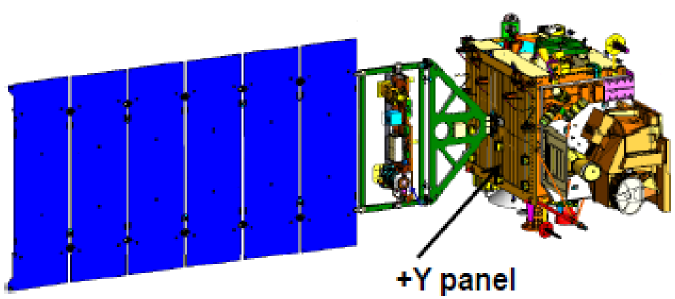
$$G = \frac{1}{2\pi}\left((y-\eta)\left[(x-\xi)^2 + z^2\right]^{1/2} \tan^{-1}\left\{\frac{y-\eta}{\left[(x-\xi)^2 + z^2\right]^{1/2}}\right\} + (x-\xi)\left[(y-\eta)^2 + z^2\right]^{1/2} \tan^{-1}\left\{\frac{x-\xi}{\left[(y-\eta)^2 + z^2\right]^{1/2}}\right\} - \frac{z^2}{2}\ln\left[(x-\xi)^2 + (y-\eta)^2 + z^2\right] \right)$$

http://www.engr.uky.edu/rtl/Catalog/index.html

Computing View Factors

- A flat surface has a total possible "hemispherical" view, with surface area $2\pi(r^2)$.
  - A steradian is defined as a "square radian" of area, so a perfect view is a "2π steradian" or F=1.0 view
- If you think of the flat surface as a radiator looking to space, anything that is within its "hemispherical" view to space reduces its view factor to space, and therefore its ability to radiate heat

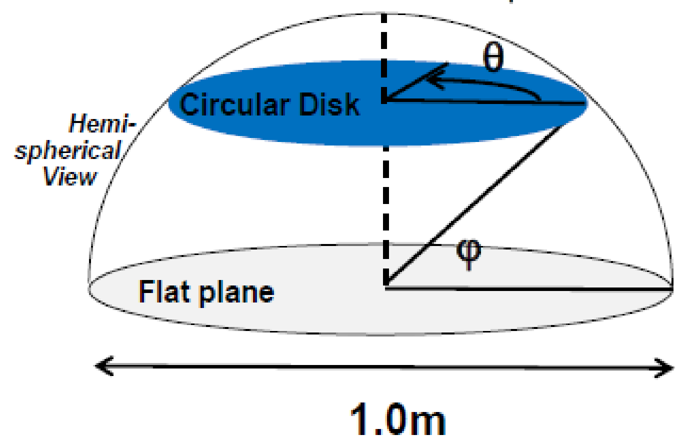
Related Fact



The solar array wing on the GOES-R (weather) satellites is in the view of the +Y panel radiator

- Example: View from a plane to a circular disk

$\varphi = 45° = \pi/4$



$$Area = \int_0^{2\pi}\int_{\pi/4}^{\pi/2} r^2 \sin\varphi \, d\varphi \, d\theta$$

$$Area = r^2 \int_{\pi/4}^{\pi/2} \sin\varphi \, d\varphi \int_0^{2\pi} d\theta$$

$$Area = r^2[-\cos\varphi]_{\pi/4}^{\pi/2}[\theta]_0^{2\pi}$$

$$Area = r^2[-(0)-(-0.7071)][2\pi - 0]$$

$$Area = r^2[0.7071 * 2\pi]$$

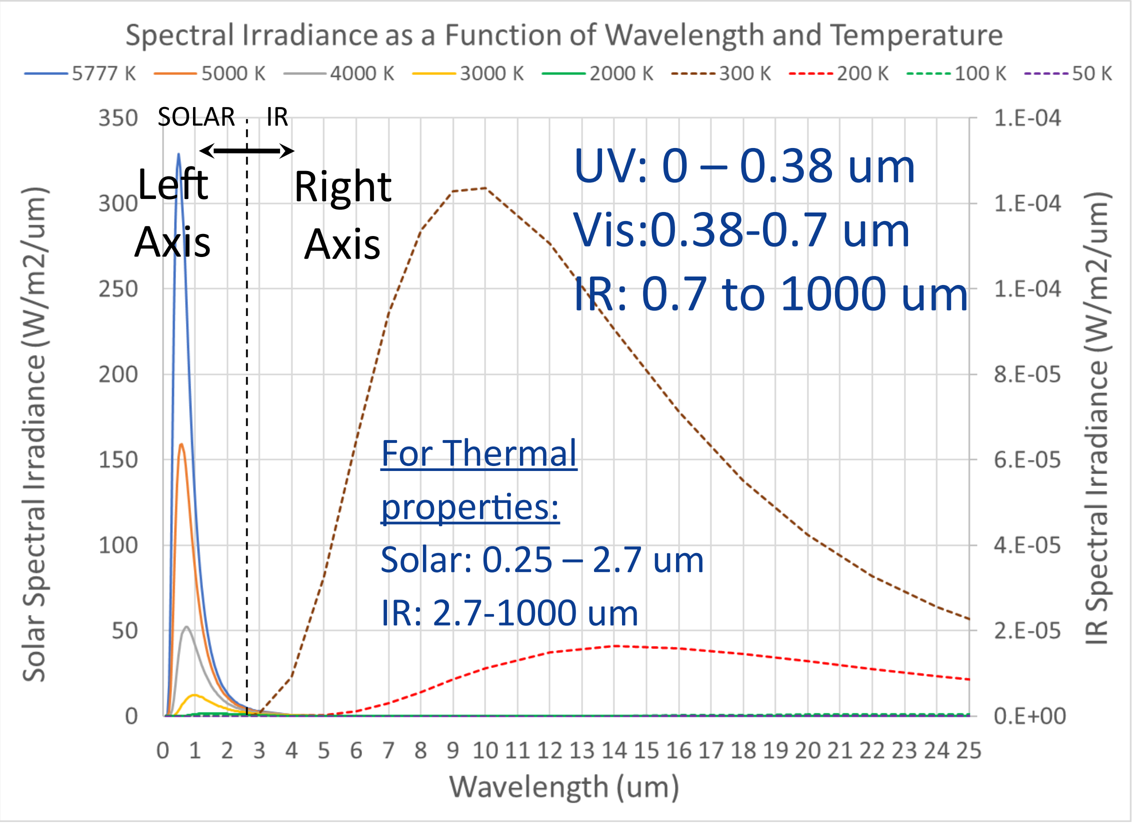
$$Area = 1.4142\pi r^2$$

$$\boxed{VF = \frac{Area}{Area_{HEMISPHERE}} = \frac{1.4142\pi r^2}{2\pi r^2} = 0.7071}$$

ENAE 691 Spring 2019

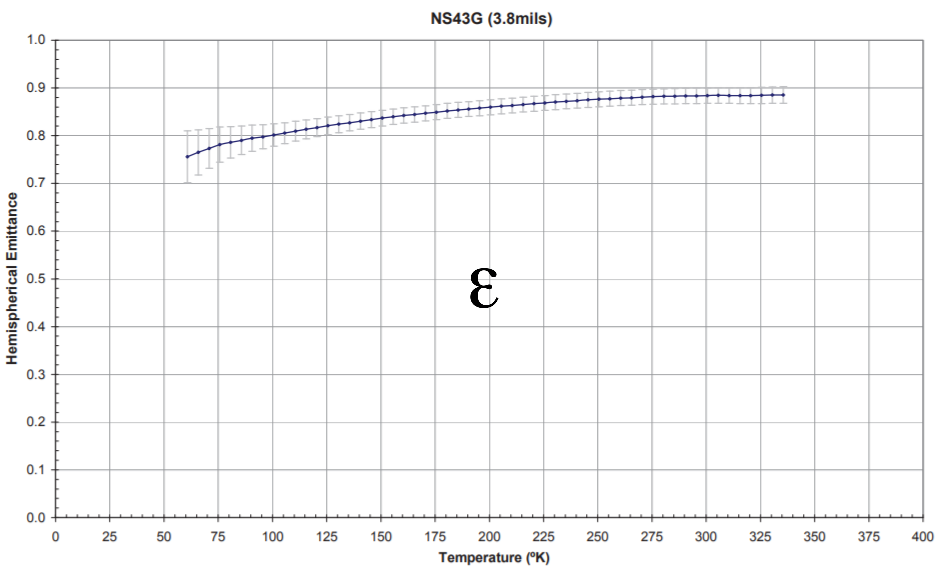
Spectral Dependence of ThermoOptical Properties

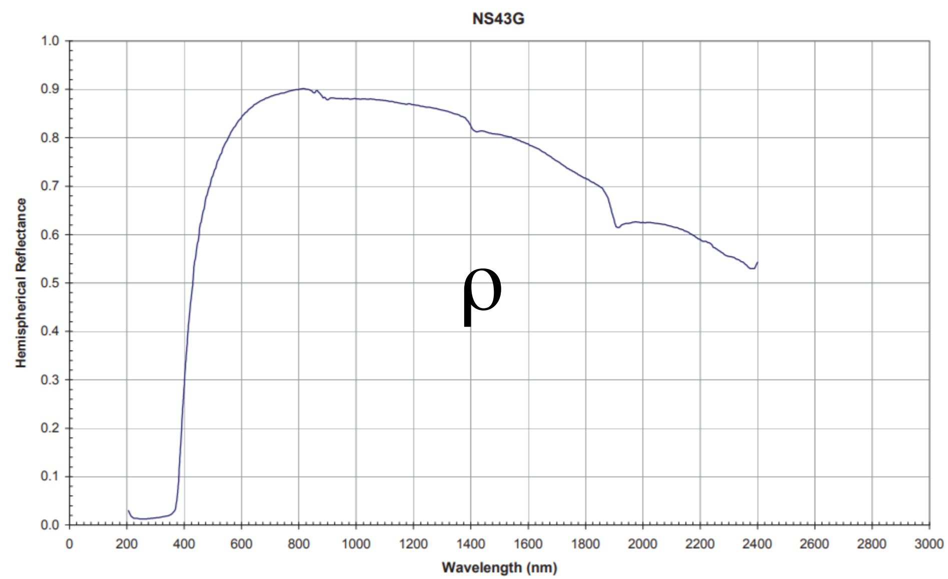
- As discussed earlier, there are two main external sources of heating on a spacecraft: Solar (incl Albedo) and IR (Planet and Spacecraft Surface radiation)
- Plotting the Spectral Irradiance for varying temperatures shows the differences in the radiation wavelengths for solar heating vs. IR heating
- This is important considering that absorptivity is also wavelength dependent
- Essentially, the properties can be banded into the IR α, τ, ρ and the Solar α, τ, ρ
- For thermal equilibrium, $\varepsilon = \alpha$



Spectral Coating Example

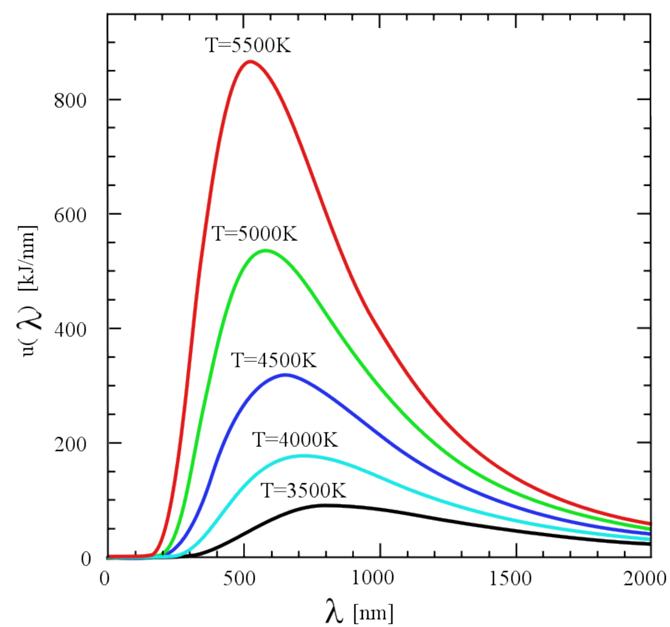
- Examine the spectral properties for NS43G white paint for emittance (60-300 K) and reflectance (0-2.4 um) from NASA/TP–2005–212792
- Note that the integration for emittance as a function of wavelength has already been done to yield an emittance as a function of temperature
- But the reflectance from 0.2 to 2.4 um (200 nm – 2400 nm) yields about 0.74 when integrating the area under the curve
- This gives a gray body solar absorptivity of about 0.26





Radiation Summary

- ***Radiation is a very important mode of heat transfer for spacecraft***
  - *Radiation – electromagnetic waves of energy emitted as a function of temperature and absorbed by other surfaces*
  - *Thermal Radiation is emitted in all directions from all objects above 0 K*
  - *Higher temperature objects (like the sun) emit far more radiation than colder objects*
    - Furthermore, the radiation is emitted over a range of wavelengths and the profile depends on the temperature of the emitting surface
  - *Emitted energy that reaches a surface is either reflected, transmitted, or absorbed*
    - The thermo-optical properties which govern these relations are also wavelength dependent
    - Typically, thermal assumes grey-body behavior, meaning that the absorptance, reflectance, and transmittance are all wavelength independent over the expected wavelengths for a mission
    - Thermal typically works in α for absorptance in the solar spectrum and ε for absorptance in the IR spectrum
    - α is the difference between a black shirt (high α) and a white shirt (low α) on a hot day
    - ε is also used for emission in the IR spectrum, where most spacecraft tend to operate (we are not as hot as the sun)
- ***The view factor (% of 360° hemispherical field of view) to the emitting source also plays a large role in the energy transfer***
  - *Just because the sun <u>is in</u> our field of view does not mean it occupies the <u>entire</u> field of view*
    - Much of our field of view in orbit is to deep space, with a background temperature of around 4 K
    - Hence, we can still reject heat to the overall effective cold temperature even when viewing the sun



Special Heat Transfer Considerations

Interface Conduction:

The heat transfer across a joint or interface can be a mixture of conduction, radiation, and convection. However, in most cases it is modeled as only a conductive process and the heat flow is described by:

$$Q = A_c h_{if} \Delta T$$

Where:

- h_{if} - interface conductance
- A_c - contact area
- ΔT – Temperature difference between two locations

Interface conductance is a function of materials, temperature, contact pressure, and surface finish. An interstitial or filler material (i.e. ChoTherm, Nusil, eGraf, Grafoil, indium foil, gold foil) can be used to enhance interface conduction. Typical ranges 0.1 to 2 W/in² K (Bare Joint to Good thick filler)

Special Heat Transfer Considerations

<u>Radiation Through Blankets</u>

Heat transfer through a blanket is modeled as radiation using the following equation:

$$Q = \sigma A \varepsilon^{*} (T_i^4 - T_o^4)$$

Where:

- ε^* - effective emissivity of the blanket (typically 0.01 – 0.05)
- σ - Stefan Boltzman Constant (5.67E-8 $W/m^2 K^4$)
- A - area of the blanket (m^2)
- T_i - absolute temperature of the inner layer (K)
- T_o - absolute temperature of the outer layer (K)

Can't narrow the ε^* range until testing

"Stack" parameters for analysis

Special Heat Transfer Considerations

<u>Backloading or Equivalent Sink Temperatures</u>

- Sometimes, the radiative environment around a component or instrument is specified for design purposes. This may be the case for an instrument or component, where the accommodation on a particular spacecraft is represented by a set of heatloads (Backloads) or temperatures in particular directions (Equivalent Sinks)
- For example, a spacecraft vendor might specify the effective temperature scene for 6 sides of box that surrounds the component. These temperatures would then be used for design purposes to locate radiators or blankets based on the optimum directions for heat rejection
- Similarly, later in the project life cycle when some models have been delivered, the spacecraft vendor may provide the incident IR radiation from all surrounding surfaces on the component as Backloads, to allow representation of the integrated environment in a stand-alone component model.
- The equations for both are shown below, where the summation is for all j where j is <u>*not*</u> a part of the component and each i <u>*is*</u> a part of the component:

$$Q_{BL} = \Sigma\ (\sigma\, \mathrm{Radk}_{ij}\, T_j^4) \quad \text{and} \quad T_{sink} = [\Sigma\ \{(\sigma\, \mathrm{Radk}_{ij}\, T_j^4) + Q_{env}\} / \Sigma\ (\mathrm{Radk}_{ij}) / \sigma\ ]^{0.25}$$

- This technique is often applied when a spacecraft vendor does not wish to provide a complex, integrated model to component vendors

Special Heat Transfer Considerations

Energy Storage/Release

- As heat is added to an object, the rate of its temperature rise is governed by its mass and specific heat. This represents an energy storage when the temperature increases
- Conversely, when an object cools, it releases some of the energy it had stored while at the higher temperature
- Energy storage is governed by the equation:

$$Q_{stored} = m * C_p * dT/dt$$

- This energy storage plays an important role in transient analyses. For steady state analysis, the dT/dt term is zero (i.e. constant T) and no energy is stored or released
- A special case of energy storage can also be found in phase change (Solid to Liquid, Liquid to Vapor). Recall from Thermodynamics that phase change is an isothermal process (i.e. constant temperature)
  - In space thermal applications, phase change is used in two phase devices such as heat pipes, where the waste heat from avionics is used to vaporize a liquid at the evaporator end. The vapor is transported via small pressure differences to the condenser end, where it releases its energy as it condenses back to liquid. This end is connected to a radiator to reject the heat to space. A wick structure then uses capillary forces to transport the liquid back to the evaporator
  - A second space-based phase change application is the use of paraffin wax to provide a short term heat sink or a longer term thermally stable interface using a solid-liquid phase change process in a hermetically sealed container

Putting it all together

- Combining the principles of Thermodynamics and Heat Transfer, the thermal performance of a spacecraft can be evaluated
- Beginning with the 1st law and Conservation of Energy for a Control volume:

  $dU/dt = Q - W$: Change in internal energy = Heat - Work
- For a system with no work (typical for a spacecraft)

$$Q_{stored} = Q_{in} - Q_{out} + Q_{generated}$$

- Recognizing that the Q_{in} and Q_{out} terms may be composed of heat transfer relations (such as conduction in and radiation out):

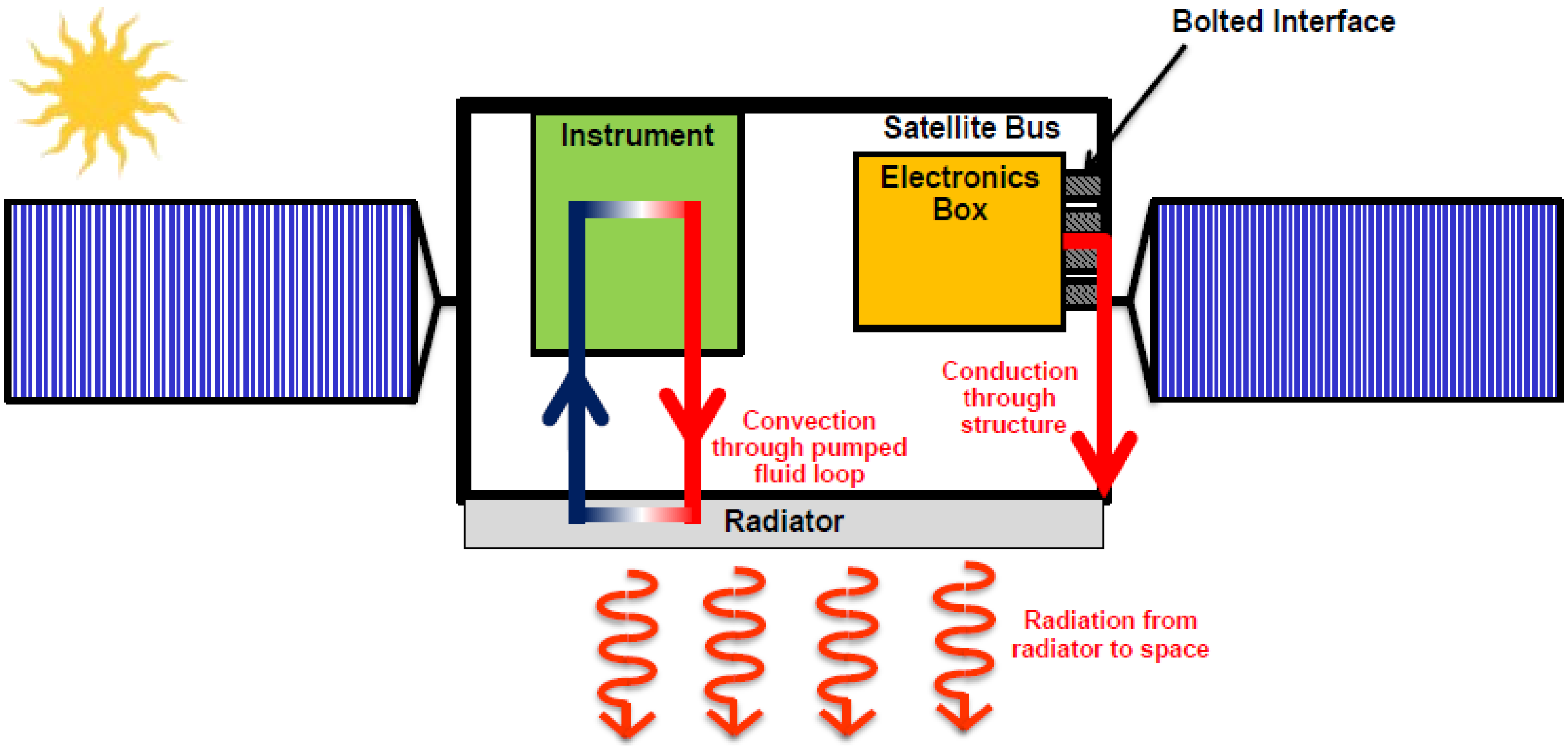
$$m\, C_p\, dT/dt = kA/L*(T_{ext} - T_{CV}) - \sigma A \varepsilon (T_{CV}^4 - T_{space}^4) + Q_{generated}$$

- Note that for thermal equilbrium (steady state), dT/dt = 0, therefore:

$$0 = kA/L*(T_{ext} - T_{CV}) - \sigma A \varepsilon (T_{CV}^4 - T_{space}^4) + Q_{generated}$$

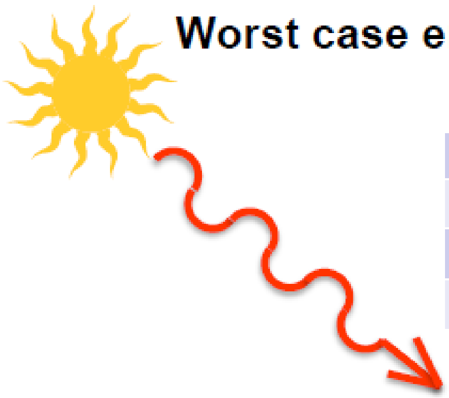
- The discretization of a thermal design into many control volumes, the generation of all the heat transfer paths between these control volumes (Radiative, Conductive, Convective) and accounting for the heat generation is the foundational basis of thermal analysis

Three Forms of Heat Transfer on a Satellite



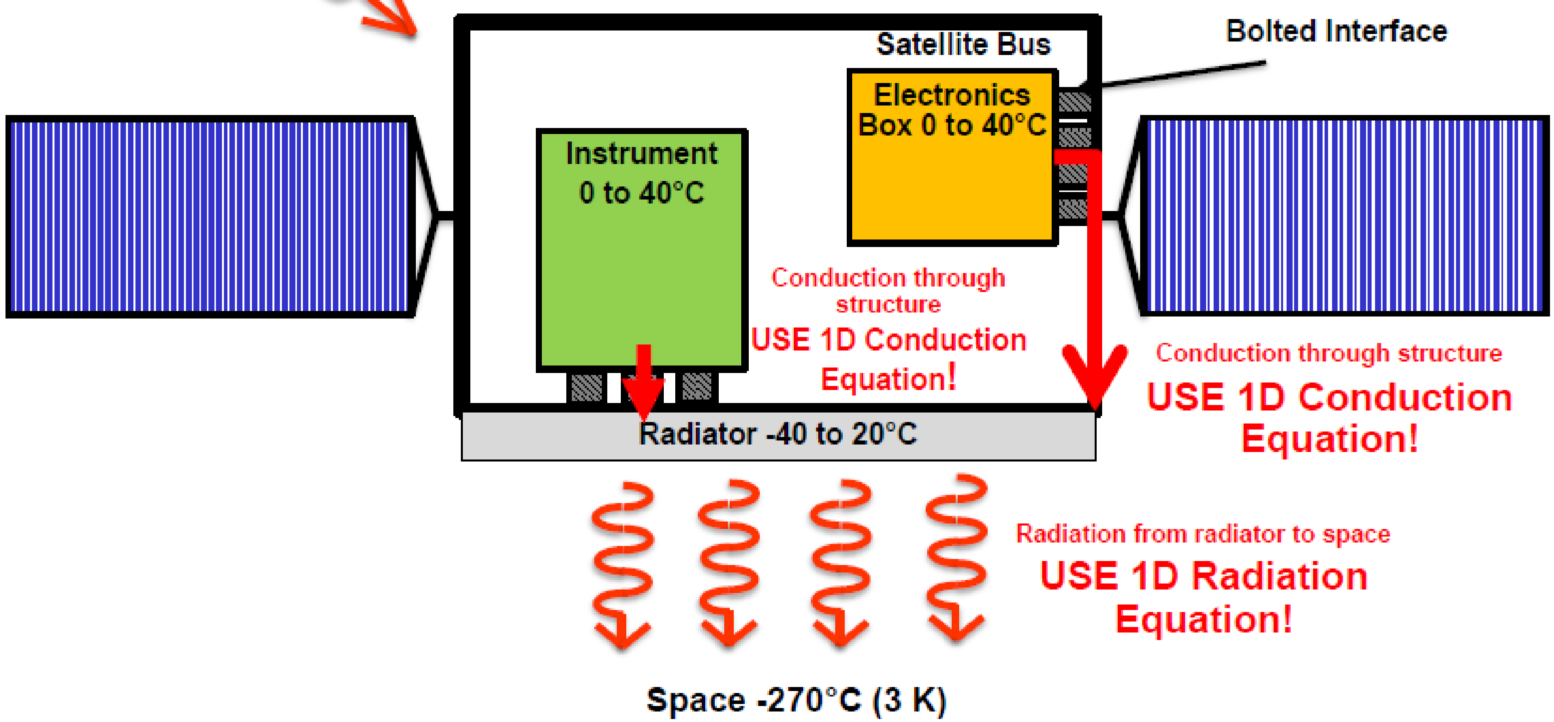
Note: For many thermal designs, radiation is negligible, with temperature differences are too small to make meaningful contributions to the overall heat flows. However, for spacecraft, with a surrounding effective background temperature of about 4 K, radiation is the only mode for the rejection of waste heat from the system since conduction and convection to a vacuum are not possible

Energy Balance: Satellite



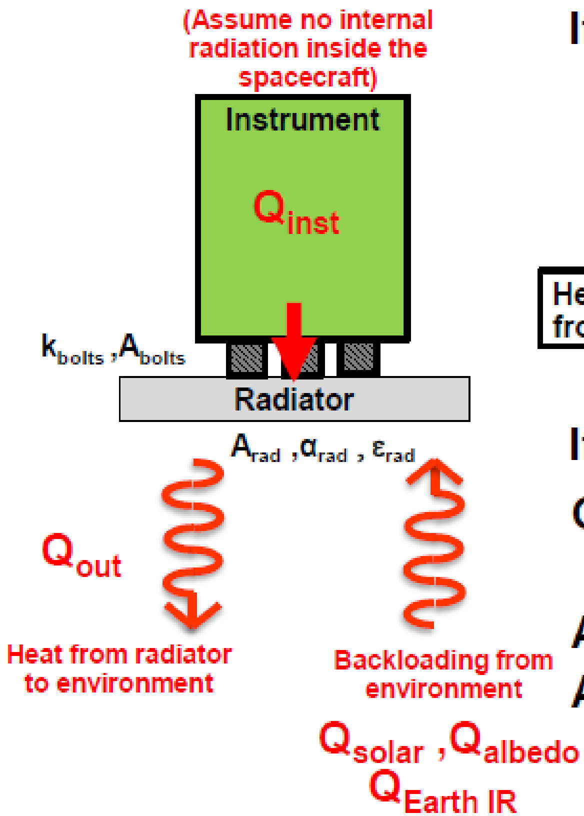
Worst case environmental loads:

	Hot Case	Cold Case
Solar Flux	1412 W/m²	1322 W/m²
Albedo	0.35	0.25
Earth IR	267 W/m²	211 W/m²
Component Powers	Max.	Min./ Off



Energy Balance: Satellite

- **Let's use the example of the instrument dissipating to a radiator, then to the environment**



If control volume was around instrument:

$$Q_{in} = Q_{out}$$

$$\underbrace{Q_{inst}}_{\text{Heat dissipation from instrument}} = \underbrace{(\#\ \text{bolts})[\,k_{bolts}\,A_{bolts}\ (T_{inst} - T_{radiator})]}_{\text{This can be used to find the bolted interface area needed to conductively transfer instrument heat, or resultant instrument temperature based on radiator temperature}}$$

If control volume was around radiator:

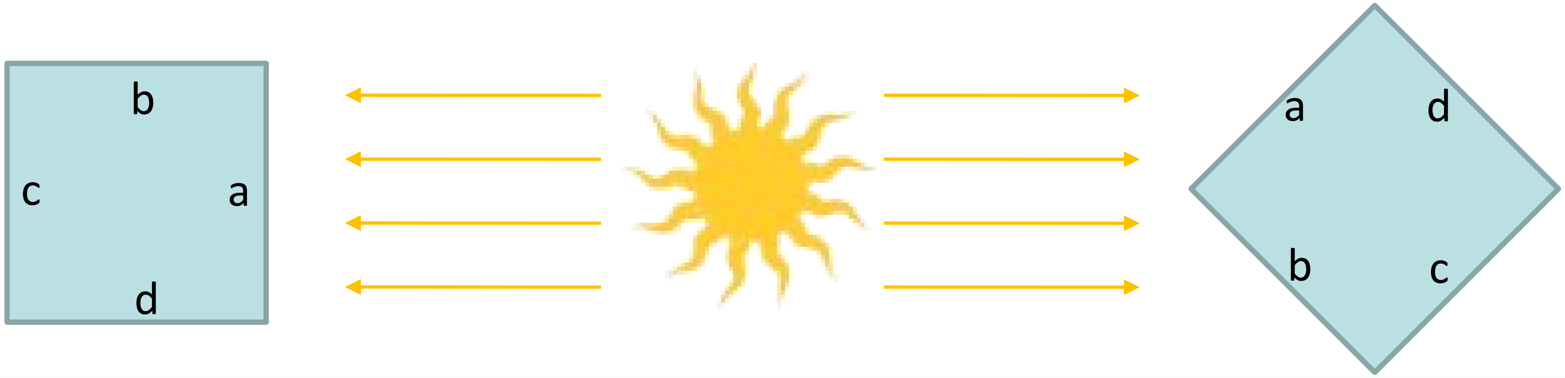
$$Q_{in} = Q_{out}$$

$$A_{P,\ Solar}\ Q_{solar}\ \alpha_{rad} + (\text{Albedo})\ A_{P,\ Albedo}\ Q_{solar}\ \alpha_{rad} + A_{P,\ Earth\ IR}\ Q_{Earth\ IR}\ \varepsilon_{rad} + Q_{inst} = \mathcal{F}\,\sigma\,A_{rad}\,\varepsilon_{rad}\,(T_{rad}^{4} - T_{space}^{4})$$

Note: A_P is Projected area normal to source vector assuming uniform flux

Square Spacecraft Bus Example

- Consider a square spacecraft bus, 1.5 m to a side and 0.75 m tall.
- Assume the panels are painted white with α =0.21 and ε=0.89
- Assume a max temperature of 35°C for heat rejection and a radiator efficiency of 80%.
- This SC is orbiting the Sun-Earth L2 Lagrange point and has a field of regard that allows for a ±45° rotation about an axis out of the page
- Assuming a Solar Constant of 1419 at Earth, which orientation yields the best over all heat dissipation rejection capability? What is the distribution per bay for each configuration?

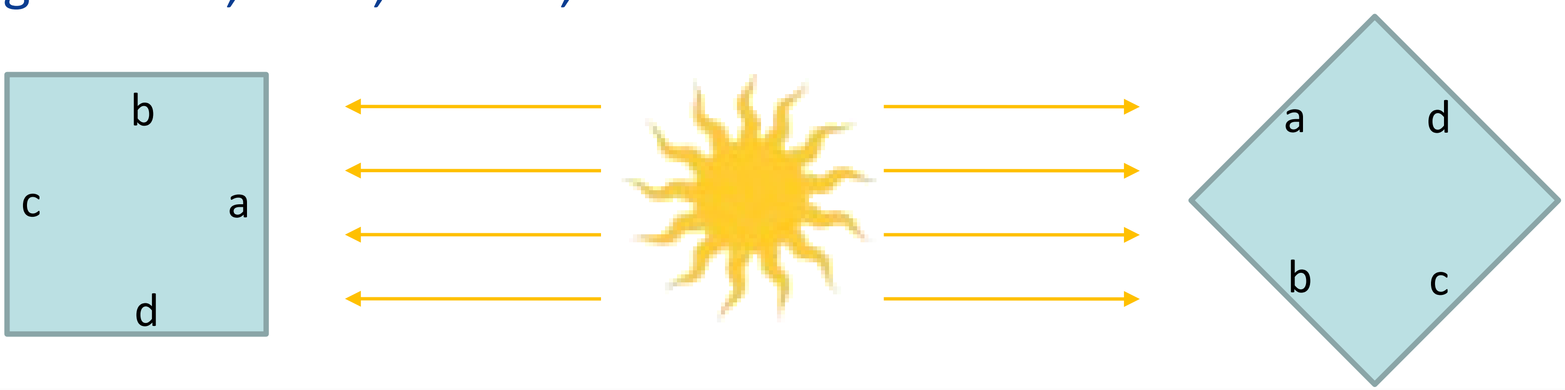


Square Spacecraft Bus Example

- Begin with a simple energy balance at steady state:

$$0 = Q_{solar} - Q_{Radiated} + Q_{Dissipated}$$

- Q_{solar} is based on the absorbed solar load. The absorbed solar flux is $(q'' * A * \alpha) = 1419 * (1/1.01)^2 * (1.5*0.75) * 0.21 = 328.63$ W for a fully illuminated side (e.g. a, left). For the angled sides, the flux is reduced by the cosine of the angle 328.63 * cos(45) = 232.39 (e.g. a,b right).
- Note that with the allowed ±45° rotation, the worst case for each bay is:
  - Left: a full, b 45, c none, d 45
  - Right: a full, b full, c none, d none

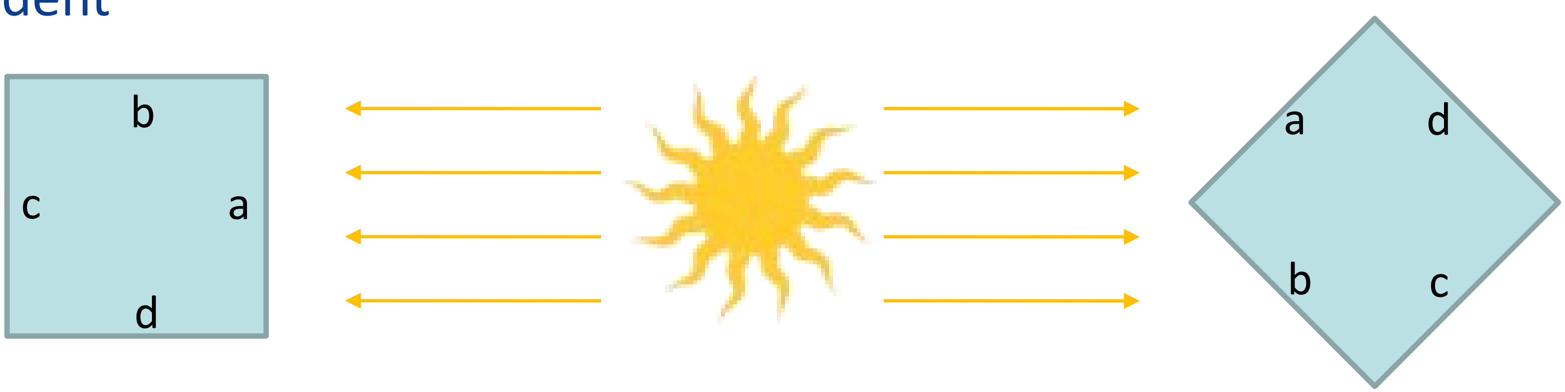


Square Spacecraft Bus Example

- The heat that is rejected is based on the simple radiation formula:

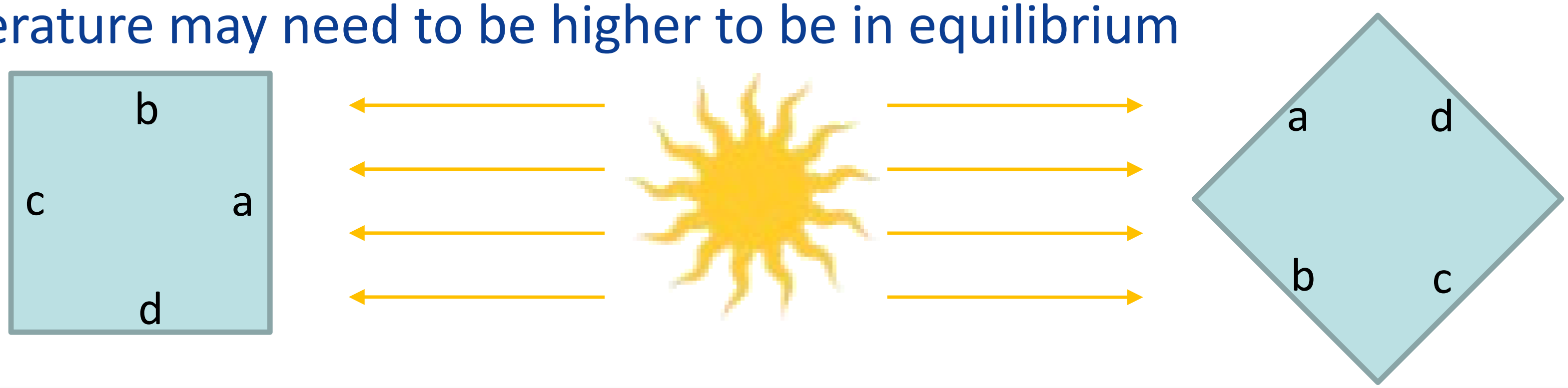
$$Q_{Radiated} = \sigma * A * \varepsilon * (T_{Rad}^{4} - T_{space}^{4})$$

- T_{Rad} is an adjusted temperature based on the efficiency where $\eta = T_{Rad}^{4} / T_{max}^{4}$ (remember to use K !). $T_{Rad} = (\eta*(T_{max}+273.15)^4)^{0.25} - 273.15 = 18.3°C$
- Solving for $Q_{Radiated} = \sigma * A * \varepsilon * (T_{Rad}^{4} - T_{space}^{4}) = 5.67E\text{-}8 * (1.5*0.75) * 0.89 * ((18.3+273.15)^4 - (4)^4) = 409.56$ W
- Note that the heat rejected does not need to be adjusted for orientation since space is in all directions, unlike the solar flux which is directionally dependent



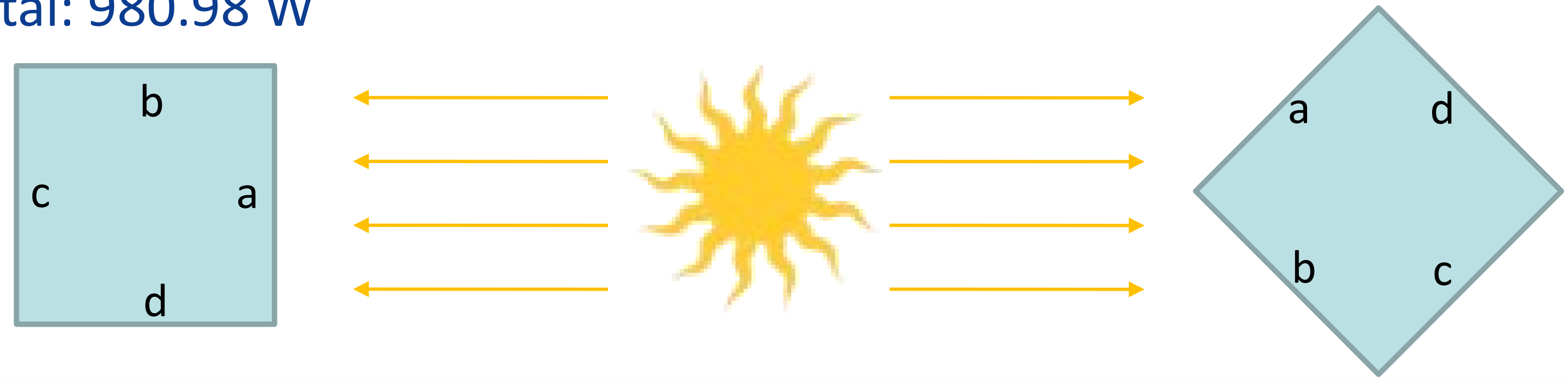
Square Spacecraft Bus Example

- The worst case for each bay will be considered independently, even though the maximum illumination of one bay does not occur simultaneously with the maximum illumination of another
- This is needed since any components in a given bay need to remain within temperature limits over any and all orientations throughout the mission
- $Q_{Dissipated}$ is what capacity remains for a given bay after rejecting the absorbed solar load. It should be noted that only the $Q_{Rejected}$ is dependent on temperature; Q_{Solar} is not. If the rejection temperature is too low, it may not be possible to reject the absorbed load; consequently, the temperature may need to be higher to be in equilibrium



Square Spacecraft Bus Example

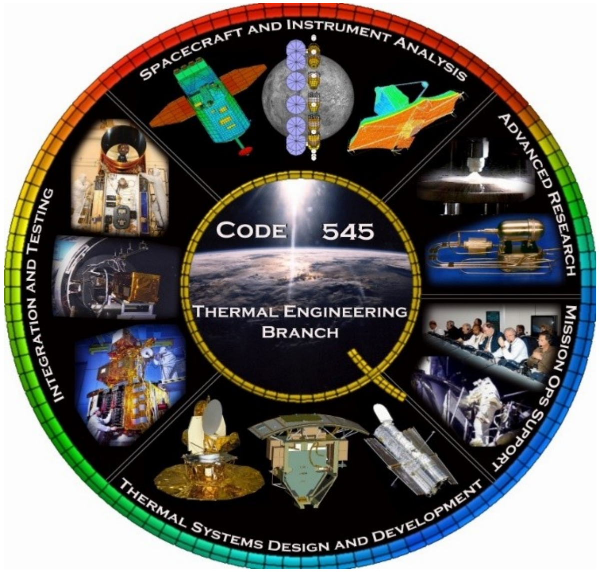
- For the left design, the $Q_{Dissipations}$ are:
  - a: 409.56 - 328.63 = 80.93 W
  - b,d: 409.56 - 232.39 = 177.17 W
  - c: 409.56 - 0 = 409.56 W
  - Total: 844.83 W
- For the right design, the $Q_{Dissipations}$ are:
  - a,b: 409.56 - 328.63 = 80.93 W
  - c,d: 409.56 - 0 = 409.56 W
  - Total: 980.98 W



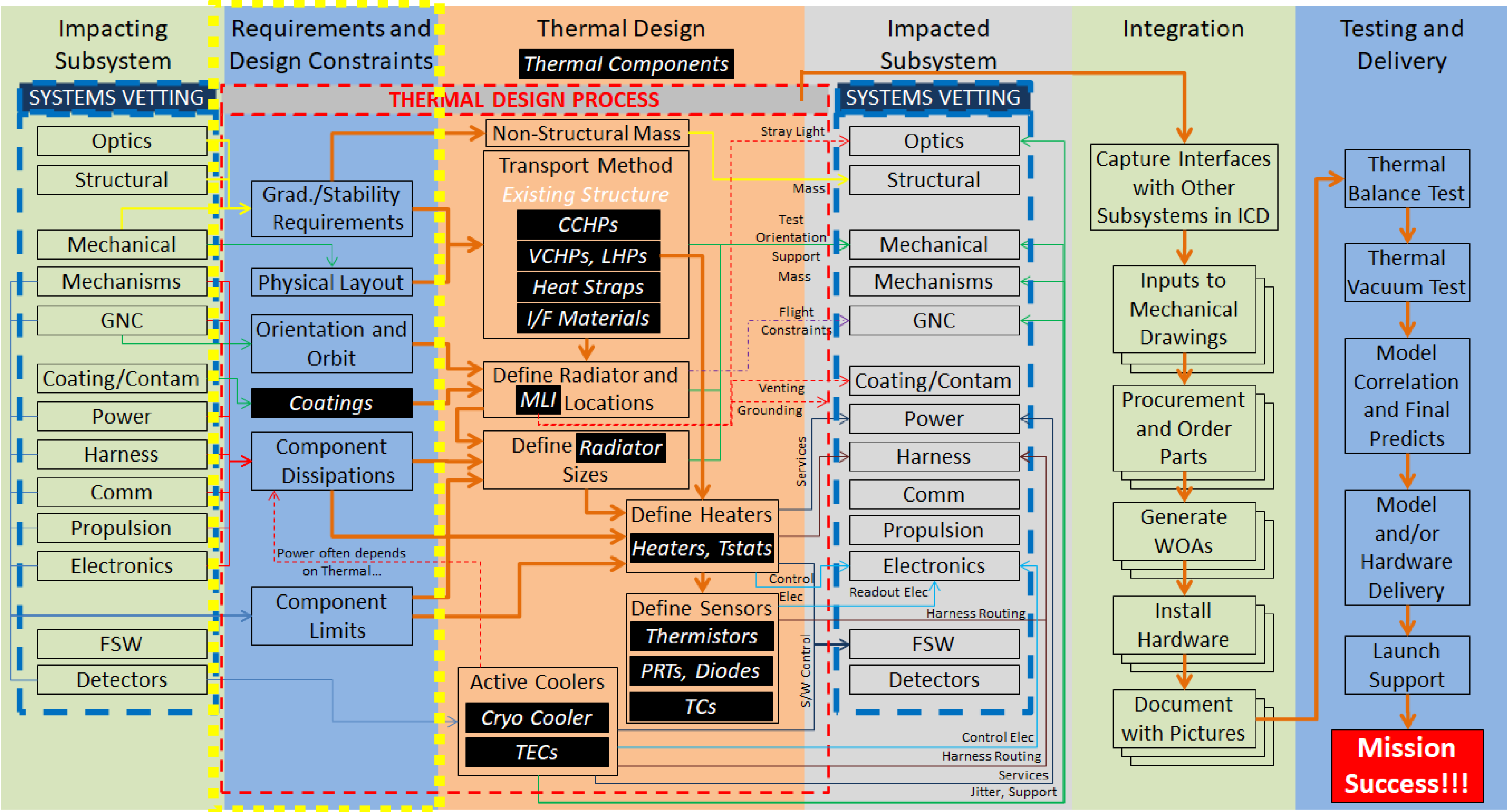
Square Spacecraft Bus Example

- So, the right design is the clear winner, correct?
  - Not necessarily. Note that the heat rejection capabilities of right bay a,b are markedly less than c,d. If you had components whose dissipations exceed 81 W, they could not go in those bays
  - However, this limitation only applies to bay a in the left design. So, the optimum design depends on more than just the ability to reject heat, it also depends on the ability to lay out the components in the design
  - Another consideration is heater power for cold cases. It is likely that the right design would only need heaters for a,b (since c,d) never see sun, whereas the left design may need it for a, b, and d.

Thermal Design Process



Thermal Design Process Flow



Gathering Necessary Thermal Inputs

- Thermal requires inputs from other subsystems that fall into one of 5 categories:
  - *Component Operating and Non-operating Temperature Limits*
    - *These* **should not come** *from thermal predictions*
    - *They* **should be** *based on optimum performance of the component*
  - *Component Waste Heat Dissipations*
    - *Thermal responsible for transferring waste heat to be radiatively rejected to deep space*
  - *Physical Layout of Components*
    - *CAD layout of the design*
    - *Often constrained by available packaging volumes, optical design, or electronics proximity requirements*
  - *Flight Orientation and Orbital constraints*
    - *Low Earth Orbit? Interplanetary? Lagrange Point? Sun Pointing? Field of Regard?*
    - *These mission high level requirements dictate where solar system heat sources are*
    - *The consequence is a limitation of optimum locations for radiative waste heat rejection*
  - *Stability or Gradient requirements*
    - *May require more complex heater control or additional non-structural material*

- The thermal design may begin once these are known, but sometimes it is necessary to start with some placeholders and assumptions…

Op and Non-Op Limits

- <u>Component Operating and Non-Operating Temperature Limits</u>
  - *Temperature limits should be specified by the responsible hardware engineer. In essence they represent an agreement that if thermal maintains the hardware within limits, then the performance should meet specifications*
  - *These limits will often be referred to as Allowable Flight Temperatures (AFTs)*
  - *Recall that temperature limits are one of the five inputs thermal needs to do a design. Therefore, it is not realistic to base limits on design predicts*
  - *However, there will likely be times where the initial thermal limits were specified to a wider range and the thermal design predicts them to be well within that range (e.g. considerable margin exists)*
  - *For these cases, it is reasonable to question if the test campaign needs to go all the way to the original limits or if the temperature limits could be adjusted based on thermal predicts.*
  - *It's a fair question, as there is little benefit in over testing hardware beyond its expected flight range*
  - *That said, if using limits from a previous mission without understanding this evolution, it is possible that subsequent missions may need a wider range than the previous mission*
  - *Once a component has undergone testing, it may make sense to adjust the limits to the levels seen during the testing campaign. Typically, the widest temperature levels are seen at the lowest test level*

Component Limits may not remain the same throughout a project's lifecycle. Thermal may push back against limits if they become too difficult to accommodate or if hardware changes necessitate narrower limits. The later in the lifecycle this occurs, the more of an impact it may have. *<u>Systems must be involved!</u>*

Op and Non-Op Limits (Common Hardware)

- Courtesy of Kan Yang and the Instrument Design Lab (IDL), here are some typical values that can serve as a starting point before specification by the responsible engineer:

Component	Typical Temperature Ranges (°C)				Stability range (°C, if applicable)
	Operational		Survival		
	Min	Max	Min	Max	
Electronics Boxes (Including Cryocooler Control Electronics, Digital Signal Processors, and Laser Control Electronics)	-10	40	-40	60	
Antennas	-100	100	-120	120	
Batteries	0	25	-10	35	
Mechanisms	10	40	-40	60	
Optical or Laser Bench (Near-IR, Visible, UV; often require stringent thermal stability)	5	35	-20	40	± 2
Lasers (often require stringent thermal stability)	20	40	-20	60	± 1
RF Components (Analog)	-10	40	-25	60	± 2
Cryocooler Thermo-Mechanical Units	5	45	-35	70	
X-Ray Sources	0	30	-20	50	

Op and Non-Op Limits (Common Hardware)

- Some additional estimated limits for common hardware provided by Eric Grob (Former 545 Chief Engineer):

Component/Subsystem	Operating Temp (°C)	Survival Temp (°C)
Digital Electronics	0 to 50	-20 to 70
Analog Electronics	0 to 40	-20 to 70
Batteries	10 to 20	0 to 35
Infrared Detectors	-269 to –173	-269 to 35
Solid-State Particle Detectors	-35 to 0	-35 to 35
Momentum Wheels, Motors	0 to 50	-20 to 70
Solar Panels	-130 to 125	-130 to 125
Thruster Valves (non-firing)	0 to 40	-10 to 50
Propulsion Tank	0 to 40	-10 to 50

Op and Non-Op Limits (Detectors)

- Courtesy of Kan Yang and the IDL, here are some typical values for *detectors* that can serve as a starting point before specification by the responsible engineer:

Wavelength Range	Portion of Electromagnetic Spectrum	Example Detector Types	Typical Operational Temperatures (K)		Thermal Stability Requirements	
			Low	High	More Stringent	Less Stringent
> 1 mm	Microwave and RF	Microwave / RF Receivers	260	310	± 0.1	± 2
25 um - 1 mm	Sub-mm wavelengths / Terahertz range	Heterodyne Receiver (SIS, HEB), TES bolometers	< 1	40	± 0.1	± 1
2.5 um - 25 um	Mid-Infrared to Far-Infrared	HgCdTe, TES, Ge:Ga Photoconductors	< 1	100	± 0.001	± 1
750 nm - 2.5 um	Near-Infrared	HgCdTe, InGaAs, InSb, STJ, TES, Si<1100nm	50	170	± 0.001	± 1
400 nm - 750 nm	Visible	Si CCD, Si CMOS, photodiodes, STJ	170	340	± 0.005	± 1
1 nm - 400 nm	Ultraviolet	GaN, MAMA, Microchannel	270	340	± 0.005	± 1
		EMCCD, CCD, CMOS	170	200	± 0.001	± 1
1 pm - 1 nm	X-Ray	Gas-filled, Scintillation, Microchannel, CdZnTe	270	330	± 0.1	± 5
		CCD, CMOS	170	200	± 0.001	± 1
		TES	< 0.1	1	± 0.0005	< ± 0.001
< 10^{-12} m	Gamma Ray	CMOS, Scintillator, CsI, SiPM, CCD, Strip Detectors	80	300	± 0.1	± 1

Waste Heat Dissipations

- Component Waste Heat
  - *Uncertainty in heat dissipation is by far the largest contributor to temperature uncertainty*
  - *Typical to get Current Best Estimate values (CBE) and use these for cold cases (minimum dissipation)*
  - *If no Allocation or Maximum Expected Value (MEV) is available, an uncertainty of 30% is often applied and used for Hot Cases*
  - *In the case of an active cooler (ThermoElectric, CryoCooler), the dissipation often depends on the heat removed and can be estimated from device performance curves based on the Cold Tip Temperature, Heat Lift, Reject Temperature, and Input Power*
  - *Most components have a relatively constant dissipation, with some notable exceptions:*
    - *Transponders have Receive and Transmit modes*
    - *Batteries only dissipate waste heat when there is a load (i.e. during eclipse)*
    - *Reaction Wheels dissipate less in an idle mode than when spun up to slew the spacecraft*
  - *Some component types work together and may have co-location requirements*
    - *Ka band Transmitter and Travelling Wave Tube Amplifiers (TWTA) and Electrical Power Conditioner (EPC)*
    - *Star Trackers and Inertial Reference Units (often co-located on an optical bench with stability rqmts)*
    - *Magnetic Torque Bars may be used along with a Three Axis Magnetometer*

Common Spacecraft Waste Heat Dissipations

- Many spacecraft have common hardware architectures
- However, the power dissipations tend to be very mission specific
  - Transponder power depends on distance to receiving asset (Ground Station, TDRS, DSN) as well as data rates and volumes
  - Reaction Wheels depend on the mass of the spacecraft to slew and the rates required
  - Batteries and Power Control Units depend on the loads of the attached avionics units
  - Command and Data Handling Units depend on the amount of processing needed
- That said, below is a list of common spacecraft avionics to consider, even if the power dissipations cannot be estimated without further inputs
  - Avionics: Command and Data Handling (CDH), Solid State Recorder (SSR), Deployment Safety Inhibits
  - Mechanisms: Mechanism/Gimbal Control Electronics (MCE/GCE), Actuators
  - ACS/GNC: Reaction Wheel Assemblies (RWA), Wheel Drive Electronics (WDE), Inertial Reference/ Measurement Unit (IRU/IMU), Star Tracker (may include separate Camera Head and Data Processing Unit), Three Axis Magnetometer* (TAM), Magnetic Torquer Bar (MTB)*, GPS Receiver*
  - Communications: Transponder (Transmitter/Receiver) [Ka, K, S, X bands], Traveling Wave Tube Amplifiers (TWTA), Electrical Power Conditioner (EPC)
  - Power: Battery, Power Switching Electronics (PSE), Power Distribution/Conditioning Unit (PDU/PCU)
  - Propulsion: Pressure Transducers, Catbed Heaters, Latch Valves
  - Instruments: Main/Instrument Electronics Box (MEB/IEB), Cryocooler Electronics (CCE)

** Earth Orbiting*

Physical Layout (CAD)

- Physical Layout of Components
  - *The Mechanical Engineer is most often responsible for packaging all the components necessary for an instrument or spacecraft*
  - *Thermal should provide inputs as to location preferences (e.g. high dissipation box near to radiator, isolated battery with its own dedicated thermal control system)*
  - *However, Thermal Engineers should realize other constraints on packaging*
    - Launch orientation and Aligning center of mass with Launch vector
    - Center of Gravity location for Attitude Control System
    - Fairing volume constraints
    - Harness routing space allocations
    - Optical/RF layouts (often beyond the Mechanical Engineer's purview to change)
    - Proximity requirements between detectors and readout electronics
    - Clear Field of View constraints or locations reserved for deployable components
- Work closely with the Mechanical Engineer early
  - *Accommodations are much easier to incorporate early in the design before it coalesces*
  - *Obtain CAD geometry early, even as the design is changing frequently, to update the thermal model, but realize it may be a struggle to keep the thermal model up to date with the current layout.*

Flight Orbital and Orientation Constraints

- Flight Orbital Constraints considered over the entirety of the mission
- Some terminology and customs to know:
  - *Ram (Velocity) is often in +X, Wake (Anti Velocity) is often –X*
  - *+Z is often Nadir (Planet pointing), -Z is often Zenith (Anti Planet)*
  - *These two orthogonal vectors define the Y axis*
  - *Rotations about X: Roll, Y: Pitch, Z: Yaw*
- Best to first begin with orbital constraints for the majority of mission…
  - *Altitude*
  - *Launch Date*
  - *Orbit Inclination, Right Ascension of Ascending Node, Beta Angle Range*
  - *Pointing constraints: Nadir pointing? Field of Regard?*
  - *Is a 180° yaw flip maneuver utilized at β=0 crossings to provide a dedicated "Cold" side of the spacecraft?*
- Then consider off nominal cases…
  - *Launch Profiles (Possible BBQ rolls of Launch Vehicle)*
  - *Calibration Maneuvers*
  - *Safe Hold Modes*
  - *Avoidance maneuvers (Sun, Moon, etc)*
  - *Cruise mode (interplanetary, Lagrange orbits)*

Gradient and Stability Requirements

- <u>Gradient and Stability Requirements often require careful consideration by the Thermal Engineer</u>
- Gradient Requirements are often expressed as a maximum allowable temperature difference between two spatial points
  - *Gradient requirements often derived from structural analysis and driven by either misalignments (typically of optics) or thermal stresses during cooldowns*
  - *Try to avoid accepting gradient requirements between ANY two points. This is too arbitrary and if someone wants to specify a gradient requirement, they should do the work to determine <u>where</u> the requirement should be levied*
- Stability Requirements are often expressed as a maximum allowable temperature variation over time.
  - *0.1 K stability is **<u>NOT</u>** a requirement!! 0.1 K over 10 minutes is…*
  - *Be sure to understand if it is 0.1 or ±0.1…this sometimes gets lost in translation*
  - *Stability requirements often levied for detectors or optics to reduce signal noise*
  - *Generally requires a more precise heater control scheme than thermostats provide*

First Questions

- **Once all requirements are known, a few questions should form in your mind:**
  - *How many thermal zones are needed? Can any components be co-located to simplify the thermal design?*
  - *What range of β angles need to be considered? Is there a dedicated "cold" side of the observatory based on orbital mechanics?*
  - *Where should the radiator(s) be located? How will the heat be transported to the radiators (e.g. Directly coupled to backside? Heat Strap? Heat Pipe?)*
  - *What coatings are needed and where?*
  - *What size do the radiators need to be to stay below the upper operating limit with some power contingency?*
  - *Do any components need active cooling (e.g. TEC, CryoCooler)?*
  - *What areas might require thermal isolation/insulation in the design?*
  - *How many heater zones are needed to stay above lower operating limits?*
  - *Are there any challenging stability or gradient requirements that will require complex control or additional thermal considerations (e.g. optical bench)?*
  - *Where are sensors needed for thermal control or knowledge?*
  - *Is the design concept ground testable?*
- **But before beginning to formulate a design to answer these questions, it helps to know what thermal components could be used to meet requirements…**

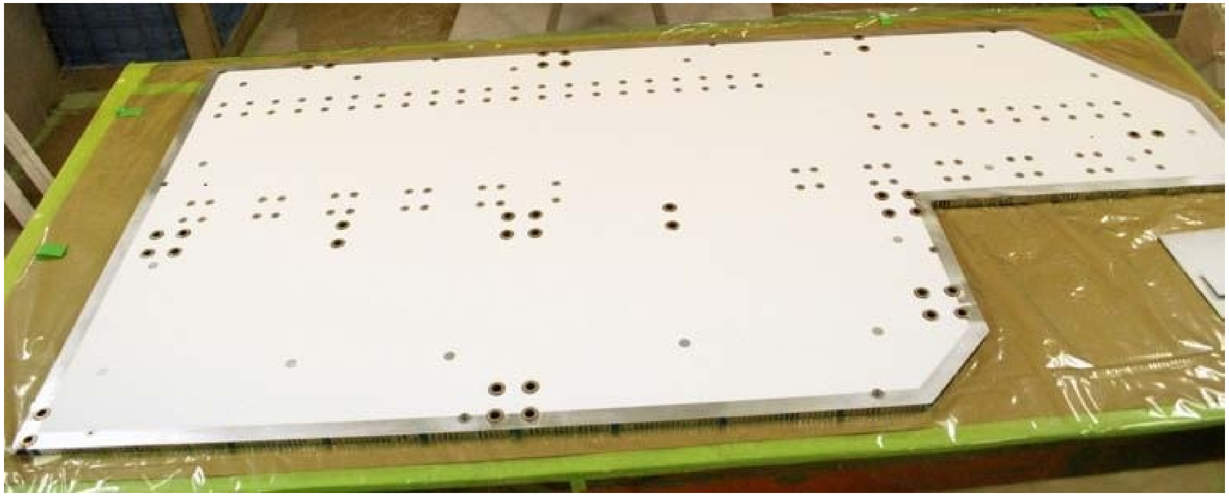
Available Thermal Components

Thermal Design Components for Space Applications

- *Radiator*
- *Thermal Coatings*
- *Heater*
- *Thermostat*
- *Multi Layer Insulation*
- *Radiative Isolation*
- *Interface Materials*
- *Constant Conductance Heatpipes*
- *Variable Conductance Heat Pipes*
- *Loop Heat Pipes*
- *Heat Straps*
- *Thermistor*
- *Platinum Resistance Thermometer (PRT)*
- *Thermocouple*
- *Silicon Diode*
- *Cryo Cooler*
- *Thermo Electric Cooler*
- *Doublers and Spreaders*
- *Annealed Pyrolytic Graphite Parts*
- *Heat Switch*
- *Louvers*
- *Phase Change Materials*
- *Mechanically Pumped Loops*

Radiator and Coatings

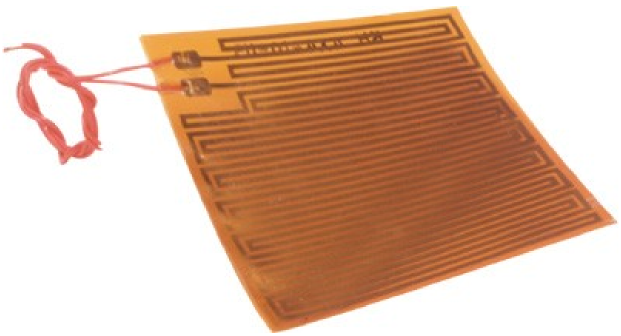
- ***Radiator –*** a dedicated structure whose purpose is the rejection of waste heat to deep space
  - Coated with high emissivity coating to maximize heat rejection potential
  - May be coated with high or low solar absorptivity coating depending on view to solar sources
  - If not existing structure, then supports are needed
- ***Coatings –*** films, tapes, paints, etc. applied to surfaces to obtain the desired thermo-optical properties for thermal control
  - Thermo-optical properties are intrinsic to the material itself (e.g. white paint, black paint, Kapton, etc)
    α – Solar Absorptivity – percentage of sun energy (Direct Solar, Albedo [e.g. reflected solar]) absorbed
  - ε – IR Emissivity – percentage of planet energy (Planetshine) absorbed
    - *Also a measure of emissive capability of a surface to reject heat via IR radiation*



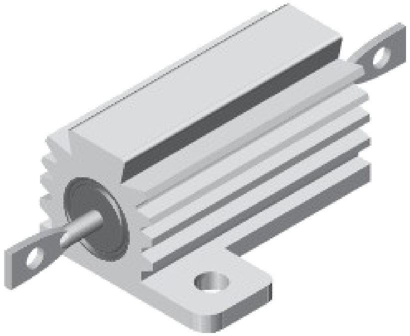
Radiator with White Paint Coating

Heater

- ***Heater –*** an electrically resistive device which dissipates heat when a current is passed through it
  - Typically either a Kapton-enclosed circuit or Dale-Ohm, cartridge style
    - *Kapton heaters often contain two traces for independent circuits. Typically applied with adhesive and overtaping with Aluminum Tape to minimize possible local hot spots. Watt density drives overall size of heater based on adhesives used*
    - *Dale-Ohm heaters typically applied with adhesive and bolted to structure. Two units required for redundancy*
  - GOLD rules requires thermal to demonstrate maximum of 70% of power usage in cold cases at minimum voltage as specified by project (or 5°C of margin to lower limits)
    - *At maximum voltage, current draw and watt density become limiting factors*
  - Heater is energized by relay (software controlled switch) or thermostat (mechanical switch)



Kapton Thin Film Heater



Dale-Ohm Heater

Thermostat

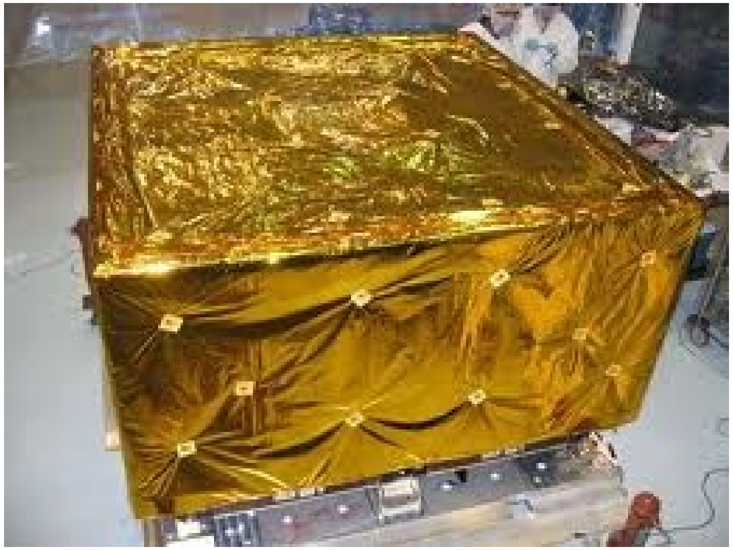
- ***Thermostat –*** a device with two materials with dissimilar Coefficients of Thermal Expansion that opens or closes an electrical circuit based on temperature
  - Mechanical part that can wear, but usually takes > 100,000 cycles before failure
  - Typically have two thermostats wired in series to prevent a single failed closed thermostat from continuously energizing a circuit
    - *If failed open, redundant side of spacecraft or instrument takes over*
    - *Could also have quad-redundant which is two parallel sets of two series thermostats (can tolerate one failed open or one failed closed without having to switch sides)*
  - Typically bonded to structure near the location of temperature interest
  - Deadband between open and close point usually around 5-7°C (9-13°F)
  - High current design (3-5 A) different than lower current design (<3 A)
  - Long lead time for procurement, need to know setpoint range before buying

Thermostats Installed on Panel

Thermostats

Multi Layer Insulation (Blankets)

- ***MLI – Multi Layer Insulation –*** aka blankets – lightweight covering of structure that impedes heat flow
  - Typically alternating layers of Dacron/Nylon mesh and Vapor Deposited Aluminum (VDA) mylar sheets with outermost layer typically Kapton/Black Kapton/Germanium Black Kapton/Stamet
  - Edges either stitched or taped
  - Grounding wires included in design; may help with EMI/EMC
  - Sometimes, Kevlar is included in blanket layup for Micrometeoroid protection
  - Mechanically supported by buttons, velcro, tie-downs, or double sided transfer adhesives (e.g. tapes)
  - If it is not a radiator, aperture, or mechanism, thermal probably wants a blanket there…



Multi Layer Insulation

Multi Layer Insulation Layup

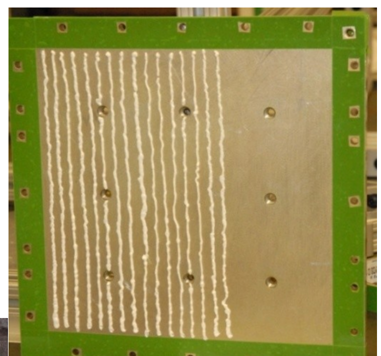
Radiative Isolation

- ***Radiative Isolation*** – this is not so much a component, but an alternative to Multi Layer Insulation
  - MLI is most often used for larger scale components
  - For much smaller components (a few inches), a blanket may not be a practical solution since the seams at the edges are typically the poorest performing part of the blanket
  - Furthermore, blankets around tight corners also do not perform nearly as well as large, flat spaces
  - Therefore, for radiative isolation of smaller parts, typically SLI (Single Layer Insulation) with low emissivity coatings (such as Vapor Deposited Aluminum: VDA) is used instead
  - Alternatively, a coating may also be applied to the part (such as Vapor Deposited Gold or Aluminum) rather than using a sheet of SLI
  - In either case, the general idea is to have a low emissivity/high reflectivity surface that reduces the amount of heat absorbed from the surroundings

Interface Materials

- ***I/F Materials –*** materials at interfaces (I/F) between components that improve heat flow; generally work better with increased pressure at contact area
  - NuSil – paste like filler, a bit “messy” to install, very good thermally, poor electrically
  - ChoSeal – sheet like filler, cut to shape, easy to install, good thermally, good electrically, retorque
  - ChoTherm – sheet like filler, cut to shape, easy to install, good thermally, poor electrically, retorque
  - eGraf – sheet like filler, cut to shape, easy to install, not-reusable, good thermally, OK electrically
  - Stycast, Eccobond, Arathane – bonding adhesive for thermostats, heaters, and thermistors

Nusil Installation



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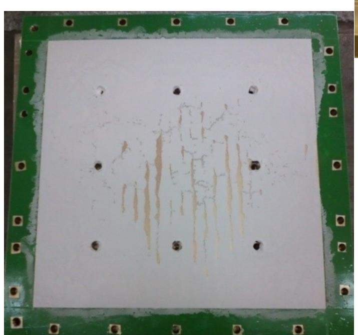
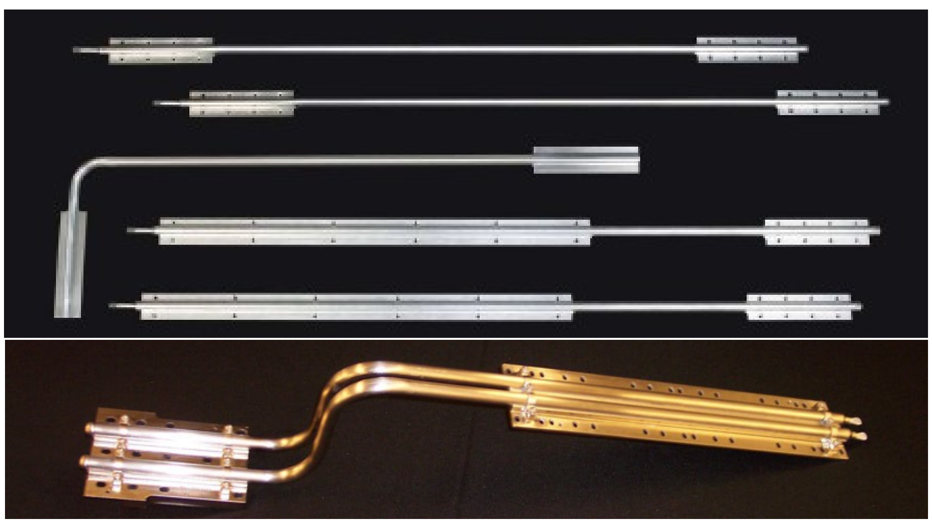


Nusil After Installation

eGraf

Constant Conductance Heat Pipe (CCHP)

- ***CCHP – Constant Conductance Heat Pipe –*** a passive, sealed system with no moving parts which utilizes an evaporation / condensation cycle to transport heat
  - Source heat evaporates working fluid (often ammonia) into vapor state
  - Pressure differences push vapor to cold end
  - Cold end typically tied to radiator where it condenses back to liquid and releases heat
  - Capillary wick transports liquid back to evaporator end
    - *Since capillary forces are weaker than gravity, heat pipe must be level during ground testing to function*
    - *Can operate in reflux mode, where gravity is the force that makes liquid return to evaporator, but this necessitates that the evaporator is below the condenser*
    - *Non-planar (3D) CCHPs are difficult to ground test and their use is not recommended by the branch*



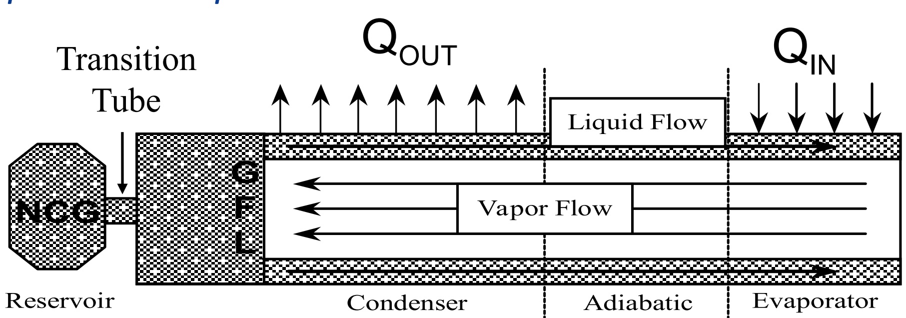
Constant Conductance Heat Pipe (CCHP)

Heat Pipe Extrusions

Flexible CCHP

Variable Conductance Heat Pipe (VCHP)

- ***VCHP – Variable Conductance Heat Pipe –*** a sealed system which utilizes an evaporation/ condensation cycle to transport heat; includes a cold biased reservoir of Non-Condensable Gas (NCG) and a heater to regulate effective length of condenser
  - Same basic operating principles as CCHP
  - Reservoir at condenser end is filled with NCG and includes a wick structure to transport condensed working fluid from reservoir back to pipe
  - When sensed temperature at evaporator is below setpoint…
    - *Heater turned on at reservoir…reservoir temperature increases…pressure increases pushing NCG into pipe…NCG impedes condensation and reduces available length for heat rejection…evaporator temperature increases*
  - When sensed temperature at evaporator is above setpoint…
    - *Heater turned off at reservoir…cold biased…reservoir temperature decreases…pressure decrease allows NCG to recede back towards reservoir…increases available length for heat rejection… evaporator temperature decreases*



Variable Conductance Heat Pipe Schematic

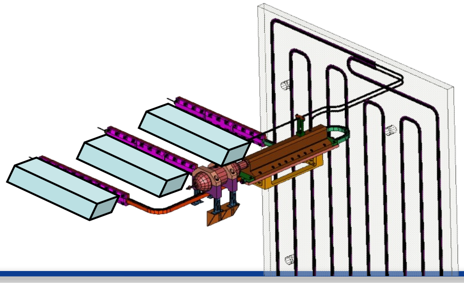
Variable Conductance Heat Pipe

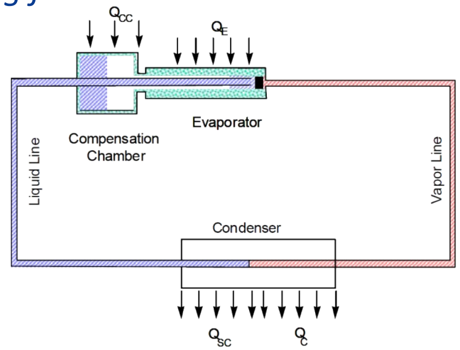
Loop Heat Pipe

- ***LHP – Loop Heat Pipe –*** a loop system which utilizes an evaporation/condensation cycle to transport much more heat than a CCHP and maintain control temperatures to ±1°C
  - Wick structure in evaporator transports liquid through evaporator. Source heat evaporates working fluid (often ammonia) into vapor state
  - Pressure differences in evaporator drive vapor through vapor line to condenser
  - Condenser typically tied to radiator where vapor condenses back to liquid and releases heat
  - Liquid return line transports liquid back to evaporator driven by capillary pressure difference from evap wick
  - Compensation chamber is a pressure regulated reservoir that can add or remove working fluid from the flow loop in response to operating temperature/power changes
    - *Wick structure transports liquid between compensation chamber and evaporator*
    - *Since only the evaporator contains the pumping wick structure, an LHP is more flexible to accommodate ground testing. Entire LHP does not need to be level, only the evaporator*
  - Expensive option, but very flexible and adjustable in flight to varying source and sink configurations
    - *Often requires dedicated controller circuit*
    - *Requires heaters to induce start up of loop*
    - *Could also require accommodation to prevent freezing of sub-cooled liquid returning from condenser*

Loop Heat Pipe and Radiator System

Loop Heat Pipe CAD Layout with Radiator





Loop Heat Pipe (LHP) Schematic

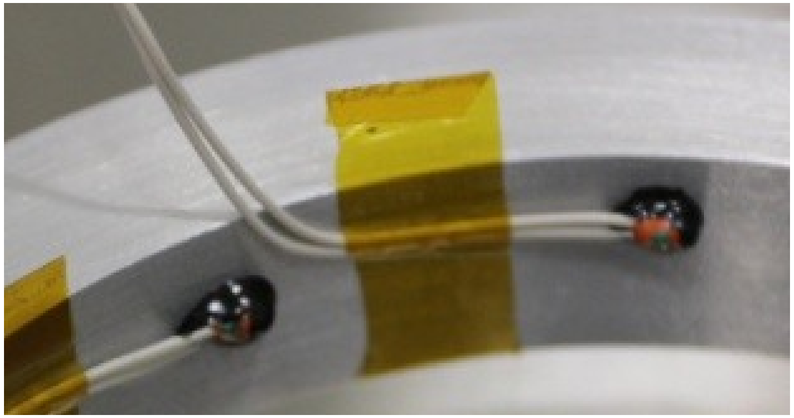
Heat Strap

- ***Heat Strap* –** flexible laminate of thin foils or braids of high conductivity material
  - Typically Copper or high purity Aluminum
    - *Encapsulated Pyrolytic graphite now also becoming more common*
  - Limited heat transport capability
  - Flexible to not carry structural load
    - *Often used to provide shortest thermal path with minimal mass*
    - *Also used to connect detectors to coolers to minimize impact of cooler on detector package (e.g. multiple load paths, vibration isolation)*

[redacted]

Thermistor and Platinum Resistance Thermometers

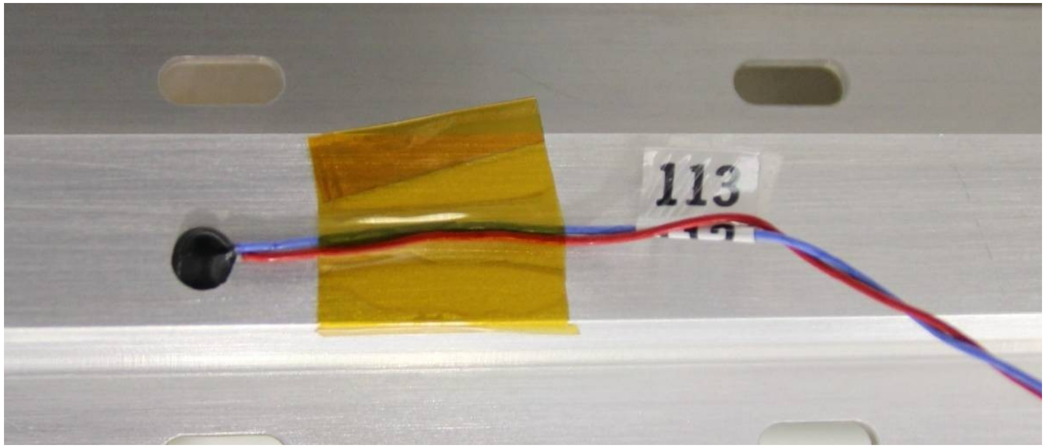
- ***Thermistor –*** a sensor whose electrical resistance changes in a predictable manner with temperature
  - Different from other Resistive Thermal Devices (RTD) in that they are typically ceramic or polymers
  - Calibration curves included with each thermistor; curves tend to be non-linear
  - Each sensor read independently on its own channel – cannot electrically combine
  - Requires a current to be passed through the thermistor to measure resistance
  - Best used for nominal temperature ranges (-60°C/213 K to +60°C/333 K)
- ***PRT – Platinum Resistance Thermometer –*** a platinum Resistive Thermal Device whose electrical resistance changes in a predictable manner with temperature
  - Similar to a thermistor, but tends to be a bit more accurate
    - *Temperature vs. Resistance tends to be fairly linear*
  - Good for colder temperature ranges (but not yet into the cryogenic range) (60 K to 333 K)



Thermistor

Silicon Diodes and Thermocouples

- ***Si Diode – Silicon Diode –*** a device where current is only allowed to flow in one direction
  - Since the forward voltage drop across the silicon diode is temperature dependent, the measured voltage can be used to infer the temperature
  - Best used for cryogenic applications (< 60 K)
- ***TC – ThermoCouple –*** a device where the junction of two dissimilar metals produces a predictable voltage based on the temperature due to the Seebeck effect
  - Less accurate than Thermistors, PRTs, or Silicon Diodes
  - Typically only used for ground testing
  - Often removed before flight
    - *If not, they must be clipped and grounded to not act as antennae for EMI/EMC*
  - Cannot go as cold as PRTs/Silicon Diodes

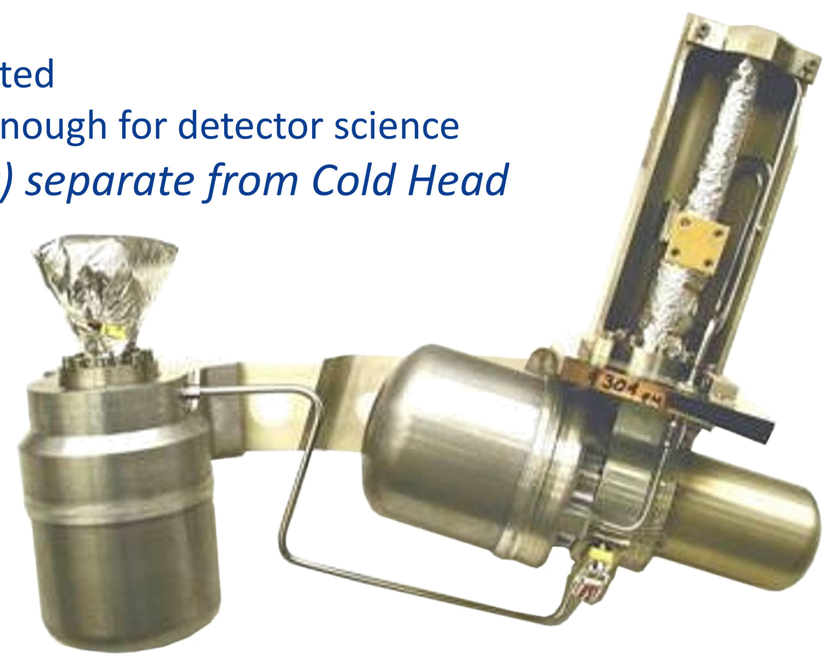


Thermocouple

Cryo Cooler

- ***Cryo Cooler –*** a mechanical device that uses a thermodynamic cycle (typically Stirling) to achieve cooling
  - Can remove small amounts of heat from colder environment utilizing power to do so
    - *Compression/Expansion of gases during cycle*
  - Power consumption depends on heat load removed, cold side temperature, and hot side temperature
    - *May require control algorithm if trying to maintain thermal stability of cooled side*
  - Most often used to cool detectors which tend to like colder operating temperatures
    - *Thermal isolation of cold side is often a challenge*
  - Often induce vibration/jitter that must be compensated
  - Expensive, but sometimes the only way to get cold enough for detector science
- *Often includes a TMU (Thermo Mechanical Unit) separate from Cold Head*

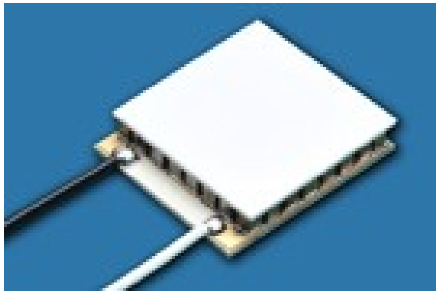
1 Stage Cryo-Cooler



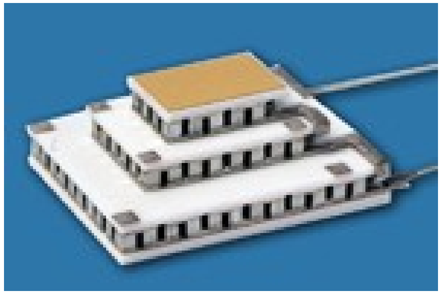
2 Stage Cryo-Cooler

Thermo Electric Cooler

- ***TEC – <u>T</u>hermo-<u>E</u>lectric <u>C</u>ooler*** – aka Peltier Coolers – an electrical device which utilizes the Peltier effect to achieve cooling, but usually only around 6-10% efficient
  - Can remove small amounts of heat from colder environment utilizing power to do so
    - *Peltier Effect – opposite of Seebeck – heat is evolved (heating) at one junction and absorbed (cooling) at the other*
  - Power consumption depends on heat load removed, cold side temperature, and hot side temperature
    - *May require control algorithm if trying to maintain thermal stability of cooled side*
  - Most often used to cool detectors which tend to like colder operating temperatures
    - *Multi-stage TECs (look like Aztec Pyramids) used to achieve greater cooling. Each subsequent layer towards the base must remove (heat removed by above layer) + (power needed to remove that heat), hence the growth of the footprint*
    - *Tend to be fairly weak in shear, so mechanical support while still providing thermal isolation is challenging*
  - Not too expensive (compared to cryocoolers), but cannot currently get much below -130°C



1 Stage TEC



3 Stage TEC

6 Stage TEC

Doublers and Spreaders

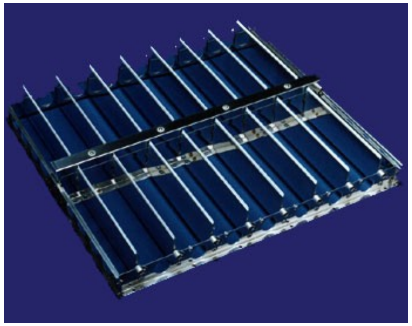
- ***Doublers and Spreaders* -** used to improve in plane conduction
  - These are generally used to reduce the thermal resistance between a heat source and the radiator (or radiative sink)
  - Doublers and Spreaders are typically thicker metal mounting plates, where the local thickness helps share heat between multiple components (e.g. Active Primary Avionics Box next to Redundant Avionics Box) or to increase the footprint of a thermal interface
  - Spreaders may also be heatpipes attached to a radiator panel or embedded in a honeycomb radiator. The use of heatpipes (and the accompanying efficiency) is often a more costly, but more mass efficient way to improve radiator efficiency over simply making the radiator thicker

- ***APG – Annealed Pyrolytic Graphite –*** a sealed aluminum component with embedded graphite sheets to improve the in-plane thermal conductivity for heat spreading
  - APG is a newer technology where a machined aluminum part is sliced in half with the center material hogged out and replaced with sheets of pyrolytic graphite.
  - The PG and the two aluminum parts are then sealed in a high temperature, high pressure process, which embedded the PG inside the part and anneals the aluminum
  - While this makes for a softer aluminum (T0 instead of T6), the embedded PG significantly improves the overall in plane heat conduction (typically by a factor of about 4)

Less Common Thermal Components at our disposal

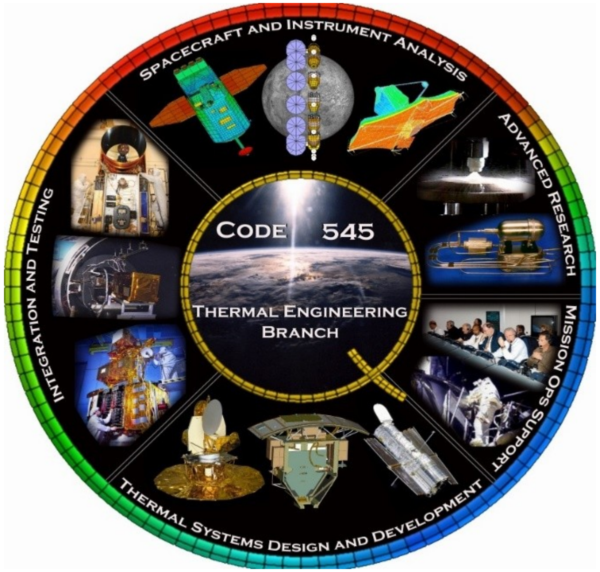
- ***Heat Switch –*** a device which passively actuates based on temperature to improve or degrade a thermal path
  - Typically uses Parafin wax which expands or contracts with temperature in combination with a spring mechanism to adjust thermal path
  - High conductivity path difficult to achieve and tend to be high mass
  - Typically used to save heater power by decoupling from radiator
- ***PCM – Phase Change Material –*** a device that relies on phase change to absorb/release heat
  - Often used to provide excellent thermal stability
    - *Phase Change is an isothermal (constant temperature) process*
  - Tends to be high mass, so not often used unless really necessary
  - Typically not a good conductor, so high conductivity vias introduced within PCM
- ***Louvers –*** mechanical device which adjusts view factor to sink
  - Like Venetian Blinds or Pinwheels
  - Similar to a thermostat, a bimetallic actuator responds to temperature and rotates the blade or fans. Not used much any more

Louver

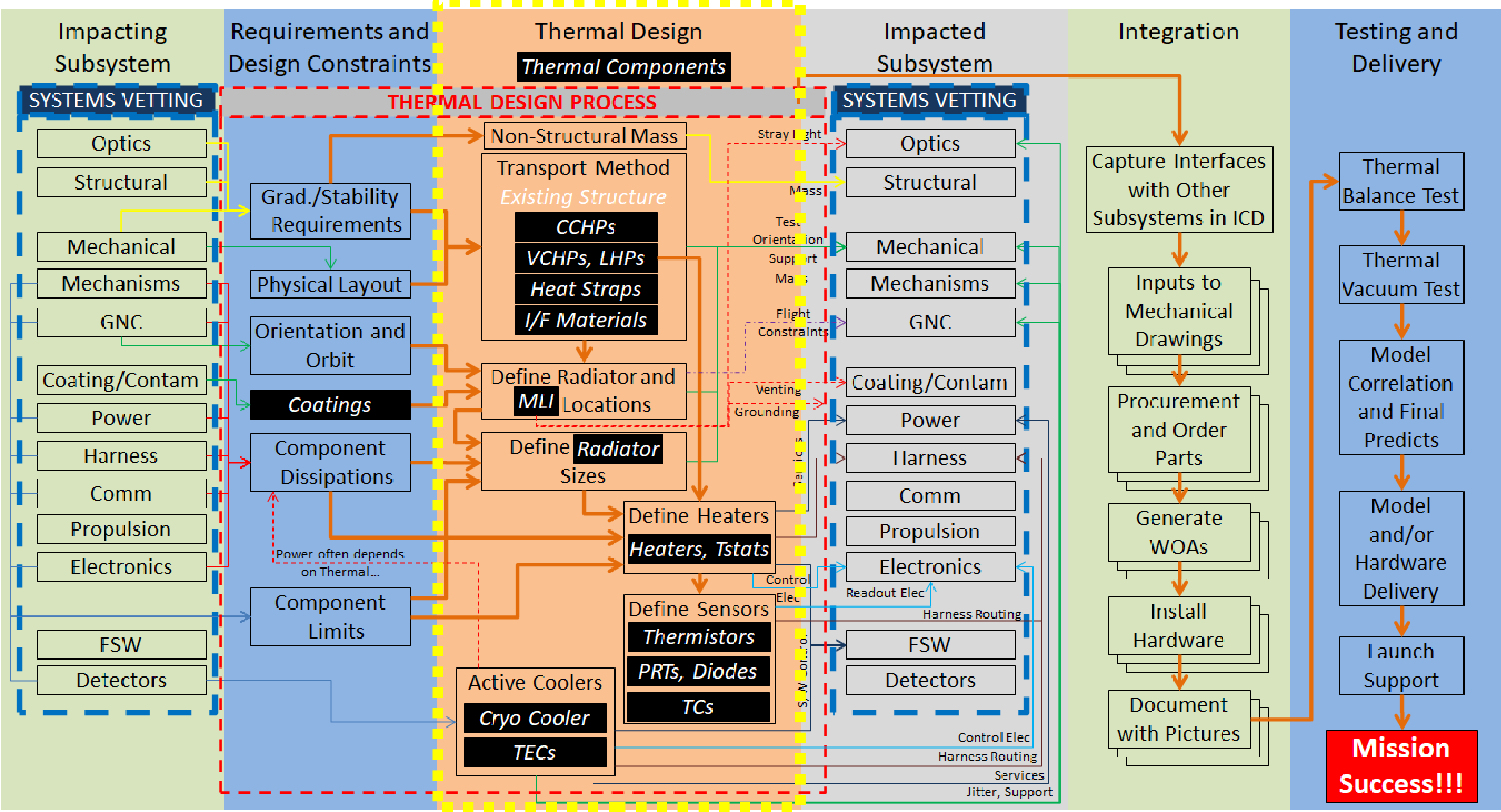


- ***Mechanically Pumped Loops –*** a mechanical device which circulates a working fluid through a closed loop system for heat absorption/rejections
  - Not subject to gravity effects like heat pipes
  - Moving parts suffer from wear, jitter, vibration isolation, etc.
  - Used on Mars/Jupiter missions by JPL

Determining the Thermal Architecture



Thermal Design Process Flow



Determining the Thermal Architecture

- **Now, back to those questions…**
  - *How many thermal zones are needed? Can any components be co-located to simplify the thermal design?*
  - *What range of β angles need to be considered? Is there a dedicated "cold" side of the observatory based on orbital mechanics?*
  - *Where should the radiator(s) be located? How will the heat be transported to the radiators (e.g. Directly coupled to backside? Heat Strap? Heat Pipe?)*
  - *What coatings are needed and where?*
  - *What size do the radiators need to be to stay below the upper operating limit with some power contingency?*
  - *Do any components need active cooling (e.g. TEC, CryoCooler)?*
  - *What areas might require thermal isolation/insulation in the design?*
  - *How many heater zones are needed to stay above lower operating limits?*
  - *Are there any challenging stability or gradient requirements that will require complex control or additional thermal considerations (e.g. optical bench)?*
  - *Where are sensors needed for thermal control or knowledge?*
  - *Is the design concept ground testable?*

A Brief Discussion on Biasing Design Parameters

- **Any design input parameters include uncertainty. It is a prudent practice to use this in a manner that generates a robust design if the uncertainty is realized during flight operation. Some biasing parameters are based on uncertainty, others are based on expected variations over the mission life**
- **Uncertainty**
  - *Solar Flux, Albedo Factor, Planet IR*
  - *Power Dissipation*
  - *Blanket effectiveness*
  - *Interface Conductances*
  - *Optical Property Uncertainty*
- **Expected Variations**
  - *Beta Angle*
  - *Optical Property Degradation*
  - *Power Profiles (based on Operations)*
  - *Solar cell energy conversion*
  - *Voltage range*

Hot vs Cold Case
Env: High Values vs Low Values
Power: High Dissipations vs Low Dissipations
Blankets: Low ε^* vs High ε^* (usually, but may depend on direction of heat flow)
I/F Cond: Low vs. High
Opt Props: High α, Low ε vs Low α, High ε
Solar Cells: Not Converting vs Converting
Voltage: Max Voltage vs Min Voltage
Beta Angle: Highest flux vs Lowest flux

- **These are considered the "Known Unknowns". To further protect against the "Unknown Unknowns", the design should maintain margin to the limits (typically 5°C of temperature margin, or 30% of heater margin)**
  - *It is much easier to blanket an oversized radiator late in the project life cycle than it is to add to an undersized radiator*

Thermal Zones

- **Examine the temperature component limits**
  - *Are any nearly the same? If so, consider if those components can be located on a radiator panel or a common interface to a radiator*
    - It is generally not desirable to group components together thermally if the temperature limits are different, since this would under utilize the capacity of a thermal control system.
    - If Component A has an upper limit of 30°C and Component B has 40°C, sizing a radiator to handle both would limit the heat rejection to a lower temperature (i.e. larger radiator)
    - Likewise, if Component A has a lower limit of 0°C and Component B has -20°C the overall heater power would need to be higher to maintain 0°C than for -20°C
  - *Fortunately, many components do tend to have the same limits of -10° to +40°C*
  - *Grouping together multiple components into a single zone also reduces the risk that power growth will exceed capacity, whereas the risk is higher for a single component/single radiator system*
  - *Batteries tend to have narrower temperature limits, while Comm Transponders tend to have wider temperature limits*
  - *Sometimes, a thermal zone may also be dictated by co-location, co-alignment, stability or gradient requirements*

Thermal Transport and Radiator Determination

- **Once you have established the nominal Thermal Zones, the next step is to determine where a Radiator will be located and how to transport the heat from the Dissipation location to the Radiator**
  - *Radiator locations are often driven by the coldest available location to effectively reject heat, usually related to orbital constraints to avoid solar illumination of the radiator*
  - *Thermal should stake our claim to these locations very early on !*
    - It is difficult to shift an entire layout to accommodate a new radiator location and thermal should be able to quickly identify where the optimum locations are for radiators
  - *Once the Radiator location is known, the next step is to determine the transport method*
    - Ideally, the back side of a mounting panel is ideal for a radiator if the orientation can work. This minimizes the thermal resistance between the dissipating component and the radiator.
    - If this will not work and the component is near to the radiator, a heat strap may be appropriate
    - Lastly, if the distance between component and radiator is larger or the heat dissipation is large, then a two-phase device (CCHP, VCHP, LJP) may be the best option
  - *Lastly, knowing the radiator location and the thermal resistance between the dissipating component(s) and the radiator (as a function of the transport method), the size may be determined to reject the known heat dissipation, while maintaining the temperature below the upper limits with appropriate margin*

What Coatings are needed?

- **Coatings are an integral part of any space based thermal design**
  - They are generally used to improve heat rejection (high ε), minimize solar absorption (low α), or minimize IR absorption (low ε) for radiative isolation
  - Coatings may have charge mitigation requirements (needing a conductivity requirement) and/or be impacted by space environment effects (atomic oxygen erosion, solar exposure, dust, handling, etc)
  - Coating values vary by mission and should eventually be specified by the GSFC Coatings Committee for all coatings in use
  - This typically includes both Beginning of Life (BOL) and End of Life (EOL), which may include degradation based on the mission duration and flight environment
  - Generally, the EOL properties for α are higher than the BOL based on expected degradation; ε is often unaffected but may include the measurement uncertainty when used in the analysis

Active Cooling Needs

- **For components with particularly low temperature limits, passive cooling with a simple radiator may not be practical**
  - *Since radiator area is proportional to Absolute Temperature to the 4^{th}, the area to cool a detector to cryogenic temperatures may not be practical to accommodate. For this case, a CryoCooler or ThermoElectric Cooler may be necessary*
    - First, the heat lift should be determined (i.e. how much heat needs to be removed). This is usually a small number on the order of 10s to 100s of mW
    - This is generally a combination of component dissipation, thermal isolation (both conductive and radiative), and wire parasitic heat loads
    - If the temperature is around -120°C or higher, a ThermoElectric cooler might be sufficient, but will likely be a multi-stage cooler
    - If the Temperature is below -120°C, a CryoCooler may be needed. At this point, reach out the the Cryo branch for assistance
  - *Any kind of active cooler will have an associated performance curve which relates the heat lift, cold tip temperature, heat reject temperature, and required input power. Thermal will need to factor this variability into any thermal analysis.*
  - *These devices tend to be quite inefficient (~6-10%...10 W input power to remove 1 W), but may be a viable option to reduce overall radiator size with the T^4 radiative relation*

Thermal Isolation Determination

- **For components with low temperature limits, the nominal design may not provide enough thermal isolation, leading to larger radiators or warmer temperatures without proper isolation**
  - *Conductive Thermal isolation is achieved by minimizing Thermal Conductivity (k) and Cross Sectional Area (A_x), while maximizing Length (L)*
    - This is often in direct contradiction with Mechanical desires, which are Small L/Large Ax
    - Material selection is often a key to thermal isolation, but material must be selected with strength in mind to meet structural requirements (Titanium, G10 good choices)
  - *Radiative Thermal Isolation can be accomplished using Coatings or Multi Layer Insulation (aka blankets)*
    - The absorption of heat can be minimized by selecting coatings (Paints, films, tapes) with a low emissivity (ε)
    - An alternative to low ε coatings is the use of Multi-Layer Insulation which is composed of alternating layers of Dacron mesh and mylar sheets to inhibit heat flow
    - The choice between coating and MLI should also consider stray light implications for optical systems. A low ε coating is highly reflective
    - In general, where there is not a radiator or an aperture, there is a blanket…

Heater Zone Determination

- **With radiators located and sized for the maximum operating temperature and the dissipation with margin, attention is turned to the cold end of the operating range. With the minimum power and a radiator sized for a hot case, it is likely heater power is needed to remain above cold operating limits**
  - *Heaters should be sized to ensure that no controlled components fall below the lower operating limit*
  - *Furthermore, the average power in the worst cold case should not exceed 70% of the heater capacity*
  - *The control of the heater should also be considered*
    - Are electronic switches needed (i.e. Flight Software control) or do mechanical thermostats suffice?
    - FSW Pros: commandable in flight, allows finer control, Cons: finite resource, requires active FSW
    - Thermostat Pros: only power feed is needed, Reliable when used in series, Cons: larger control band (usually 5-7 C between On and Off)
  - *For stability control heaters, the control authority should also be robust (i.e. the heater power needed in worst case hot cases should not be near zero)*
  - *Heater circuits are generally inexpensive enough to implement redundancy (Primary and Redundant sides), even for higher risk posture missions*
  - *Note that a portion of heater power usage is implicitly included in power budgets*
    - If the system includes power growth allowance, then the Solar Array already includes power representing the difference between Allocation and Current Best Estimate
    - e.g. Component A expects to be 50 W, but the allocation held for Solar Array sizing is 65 W to allow for potential power growth. Therefore, if the component is off and does not need more than 65 W of heater power, no more demands are placed on the Power Budget

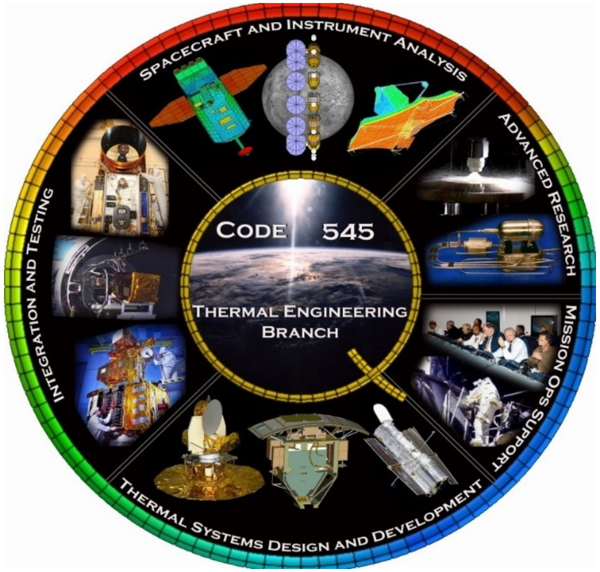
Thermal Sensor Determination

- **With radiators and heaters determined, the design is nearing completion. However, knowledge of the thermal performance during ground testing and flight is crucial and sensor layout is an important step**
  - *For most missions, thermistors are sufficiently accurate for flight telemetry*
  - *However, sometimes Platinum Resistance Thermometers (PRTs) or Silicon Diodes are needed for accuracy at lower temperatures*
  - *The need for Primary and Redundant sensors should also be considered. Like heaters, the implementation of redundancy is usually comparatively inexpensive*
  - *Any sensors used for control (Heater, Cooler) should be identified and communicated with Flight Software as well as the desired control algorithm (Thermostatic, PID, etc)*
  - *The total number of Flight Sensors should be communicated with Flight Software and the Command and Data Handling groups to ensure display and sufficient readout channels*
  - *Thermocouples could be considered for additional ground testing, but are generally not considered reliable enough for flight telemetry*
    - These may be removed prior to launch or clipped and grounded to prevent EMI issues if accessibility prevents their removal
    - With proper planning, the accommodation of test only TCs can be optimized

Considerations for Thermal Ground Testing

- **Any thermal design must consider the ability to test on the ground. This usually falls into one of two types of considerations:**
- **Ability of the Design to be tested**
  - *Does a lack of possible deployed components (Sun Shield, Solar Array) present any problems?*
  - *Are two phase devices able to function?*
    - *Constant conductance and variable conductance heatpipes must be level or with the Evaporator end of the pipe higher in elevation than the Condenser end (Reflux mode)*
    - *Are there any effects of gravity on flow through an LHP condenser?*
- **Capabilities of the Test Facility**
  - *How will the flight thermal environment be simulated?*
  - *Is a chamber shroud enough to represent the environment?*
  - *If not, are heater panels (cooled by radiative views to shroud), cryo panels (cooled by dedicated cooling lines), and thermal target plates (cooled by a cryo cooler) needed?*
  - *How many thermal zones need to be simulated in the test? Is this within the capabilities of the facility?*
  - *Is simulation of solar sources needed or will Infrared heater plates suffice?*
  - *What additional targets, sources, or equipment is needed for the instruments?*

Early Thermal Design Calculations



Radiator Sizing to Deep Space

- *To begin, the power dissipation and component limits must be known*
- *Estimate T_{Rad} based on degrading factors such as: required margin (5 K), a Transport resistance (e.g. ΔT from a strap), and radiator inefficiency*
  - *If a radiator is larger than the footprint of the heat source, then there is likely to be a gradient as heat conducts in plane away from the source and radiates to space to points on the radiator further away from the footprint of the source*
  - *The efficiency may be estimated by the $(T_{avg} / T_{max})^4$ where T_{max} represents the temperature at the input to the radiator and T_{avg} represents the average radiator temperature. Ideally, this number sound be relatively high (80-90%) or it may be necessary to make the radiator thicker or add spreader heat pipes*
  - *For example, assuming a 40°C limit, holding 5°C of margin, assuming a 3°C ΔT from the transport, and a radiator efficiency of 85% yields: T_{Rad} = 19.85°C – remember to convert to K for the $(T_{avg} / T_{max})^4$*
- *The Dissipation should also be increased, to account for potential power growth. Unless the value given is an allocation or Maximum Expected Value (MEV), 30% is reasonable*
- *Assume a reasonable, but high emissivity based on white or black paint (0.87)*
- *Begin with the basic radiative heat transfer equation and rearrange to solve for the radiator area (assuming deep space at 0 K for simplicity)*

$$\mathbf{A_{Rad} = 1.3 * Q_{Dissipation} / (\sigma \; \varepsilon \; T_{Rad}^4)}$$

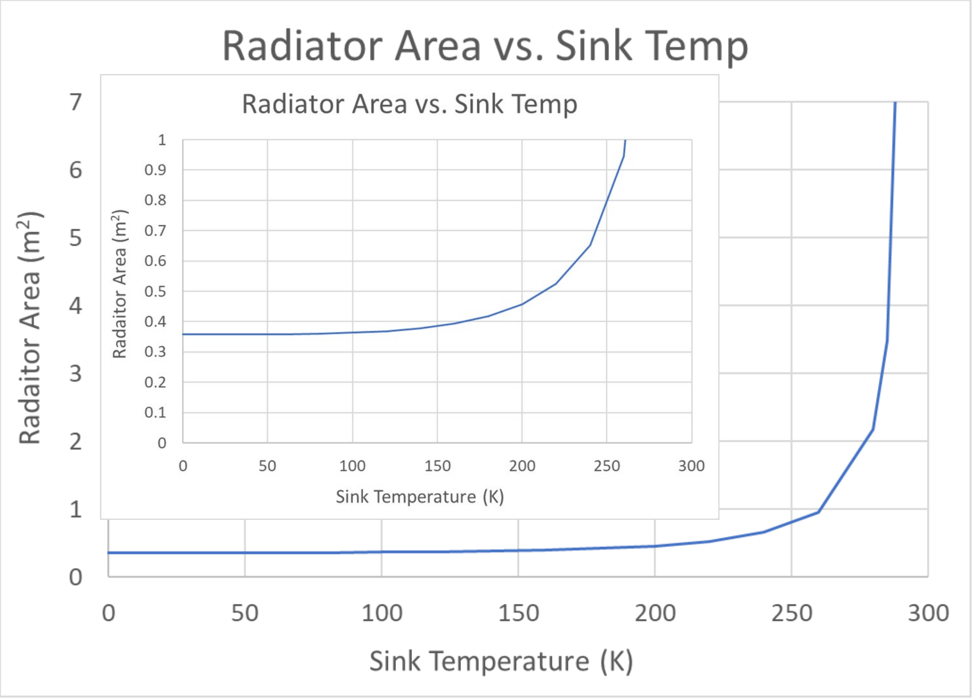
- *For a 100 W dissipation and a limit of 40°C, this suggest you need 0.3583m² of radiator area for this design (allowing for 30% power growth)*

Radiator Sizing to a Sink

- *The previous hand calc assumed a perfect view to deep space. But what if the radiator direction is not purely to deep space?*
- *The equation is adjusted to:*

$$A_{Rad} = Q_{Dissipation} / \{ \sigma \ \varepsilon \ (T_{Rad}^{4} - T_{Sink}^{4}) \}$$

- *The plot shows the impact of a varying Sink Temperature*
- *Note that sinks below about 200 K have very little impact on the radiator size for this warm a T_{Rad}*
- *It is not until the sink warms above 200 K (-73°C) that the required area increases appreciably*
- *It should be noted this holds true for components near room temperature. If T_{Rad} was much lower (for say an IR detector), then this effect may not be seen*
- *It also explains why much of our testing can be done with LN2 panels at 80 K for many room temperature avionics*



Determining the Sink Temperature

- *If a sink temperature in a given direction has been specified, then this value may be used. Some projects may have these environments already defined in various directions if they are expecting numerous competing instrument designs*
- *If the sinks are not specified, then the thermal analyst may use a simple cube model in the characteristic orbit environment with appropriate optical properties to determine the sink*
- *A massless surface with an adiabatic backside, no additional heat applied, and the appropriate optical properties will reach an equilibrium temperature based on rejecting the exact amount of heat absorbed from the environment.*
- *This temperature is effectively the equivalent sink temperature*
- *Note that this technique may also be used in larger models (using a very small square over the actual model) to determine the effective sink temperatures. These values may later be used to determine what panel temperatures should be during TV testing to emulate the flight environment.*
- *Once sink temperatures are known, they may be used for radiator sizing*
- *Once the estimated radiator size is determined, begin working with the mechanical engineer on placement and packaging*

Heater Sizing

- *Heater sizing cannot be done without first knowing the radiator size and the minimum component temperature*
- *A "cold" sink temperature may be used, but assuming a sink of zero will never produce an undersized heater…*
- *Begin again with the basic radiation equation and rearrange to solve for Q_{HTR}*

$$Q_{HTR} = \sigma \ \varepsilon \ A_{Rad} \ (\ T_{Low}^{\ 4} \ )$$

- *T_{low} is the minimum component temperature increased to account for any margin or transport losses. This also assumes that the component has no dissipation and would be applicable for a survival heater.*
- *If instead the heater is an operational heater, then any dissipation may be removed from the calculated Q_{HTR} to determine the heater size*
- *Lastly, the heater should be sized to use no more than 70% of the available capacity based on the average usage, so the actual size to model is Q_{HTR}/ 0.7*
- *For that 100 W box, assuming a lower non-operating limit of -20°C, no dissipation, the 3°C transport resistance, and the radiator size of 0.3583m^2, Q_{HTR} would evaluate to 75.9 W and the heater would be specified to 108.44 W at minimum voltage*
- *When reporting the heater power usage in the power budget, it is important to note that of the 108.44 W, 130 (100 W + 30%) should already be booked. So, while this does not place increased power generation demands on the solar array, it does require a power service capable of this power level*
- *Note that the instantaneous power would be even higher for a higher voltage, but the average power would remain the same regardless of voltage*

Hand calculations many Thermal Engineers do

- ***Step 1: Get requirements***
  - Electronics box, dissipating 15 to 40 W and needing to stay between -10°C and 40°C
  - Orbit beta angles go from 0° to 90°, nadir viewing
  - Spacecraft has provided a cold side such that it will never have direct sun, but will always have glancing view of Earth
- ***Step 2: Size the radiator***
  - Energy balance: $Q_{SRC} + Q_{IN} + Q_{HTR} = Q_{OUT}$

    $40 + Q_{IN} + 0.0 = Q_{OUT}$ (Assume no heater power is needed in hot case)
  - Environment: $Q_{IN} = B_{ij} * \varepsilon * \text{EarthFlux} * \text{Area}$ (B_{ij} to earth for surface normal to Planet is about 0.2)

    $Q_{IN} = 0.2 * 0.85 * 243 * \text{Area}$ (Hot Case Earth flux is around 243 W/m²)
  - Radiation: $Q_{OUT} = \sigma * \varepsilon * B_{ij} * \text{Area} * (T_{HOT}^4 - T_{SPACE}^4)$ (ε of 0.85 typical for radiator)

    $Q_{OUT} = 5.67E\text{-}8 * 0.85 * 1.0 * \text{Area} * (308^4 - 4^4)$ (308 K = 35°C = 40°C – 5°C margin)
  - ***Area is about 0.1 m²***
- ***Step 3: Size the heater***
  - Energy balance: $Q_{SRC} + Q_{IN} + Q_{HTR} = Q_{OUT}$

    $15 + Q_{IN} + Q_{HTR} = Q_{OUT}$
  - Environment: $Q_{IN} = B_{ij} * \varepsilon * \text{EarthFlux} * \text{Area}$ (B_{ij} to earth for surface normal to Planet is about 0.2)

    $Q_{IN} = 0.2 * 0.85 * 208 * 0.1$ (Cold Case Earth flux is around 208 W/m²)
  - Radiation: $Q_{OUT} = \sigma * \varepsilon * B_{ij} * \text{Area} * (T_{COLD}^4 - T_{SPACE}^4)$ (ε of 0.85 typical for radiator)

    $Q_{OUT} = 5.67E\text{-}8 * 0.85 * 1.0 * 0.1 * (268^4 - 4^4)$ (268 K = -5°C = -10°C + 5°C margin)
  - ***Q_{HTR} is about 6.7 W; to have 6.7W with 70% duty cycle, 10 W heater needed***
- ***Step 4: Verify the hand calcs with more detailed model***
  - Sometimes we don't even have a good feel for the B_{ij} to the sun or Earth
  - In these cases, we typically model a cube in a representative orbit with α=1 and ε=1 to get the loads

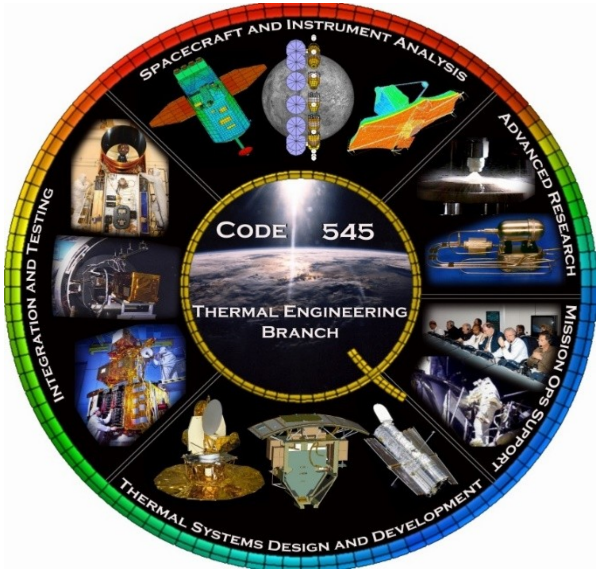
Establishing the Worst Case

- *To determine the worst case, it is typical to perform a sweep through a range of β angles or Field of Regard positions if the worst case hot or cold is not intuitively obvious*
- *For β angles, usually about 7-15 points throughout the range is sufficient*
- *For Field of Regard, usually evaluating the corners, center, and midsides is enough*
- *Once the worst case is found, a sweep through all other cases usually does not need to be performed every time the analysis is run. While the design may change, the environments generally do not unless a major design change necessitates revisiting (e.g. new radiator or location)*
- *It should be noted however, that what may be the worst case for one component, may not be for all components. So, once the sweeps are complete, a subset of worst cases should be identified, and the design checked against these cases*

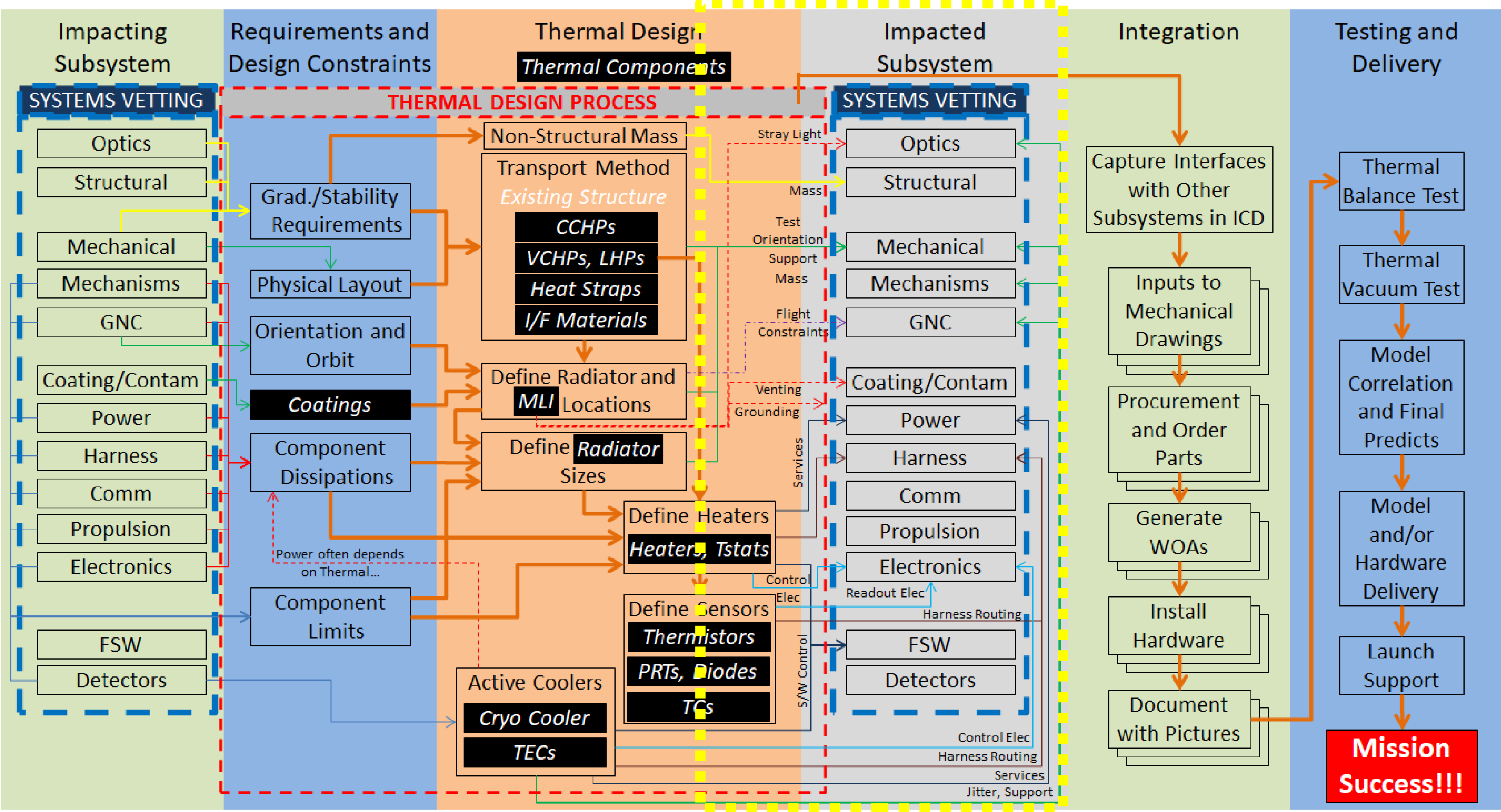
Next Steps

- *Once the initial estimates are made for temperature zones, radiator sizes, and heater sizes, the mechanical engineer may begin to lay out the overall spacecraft or instrument architecture*
- *Along with inputs from all other disciplines, the physical layout of the overall design begins to take shape*
- *As this matures, the thermal engineer should begin a more detailed model to verify that the early estimations were reasonable*
- *Discussions with other disciplines is also needed regarding the necessary accommodations to implement the thermal design, such as power services and harness*
- *These early radiator and heater sizings lay the foundation for the numerous iterations and updates of the design throughout the project life cycle, but are by no means the end of the process*
- *The next section details some of the accommodation considerations and interfacing with Systems Engineering and the Project*

Accommodation of Requirements from Thermal

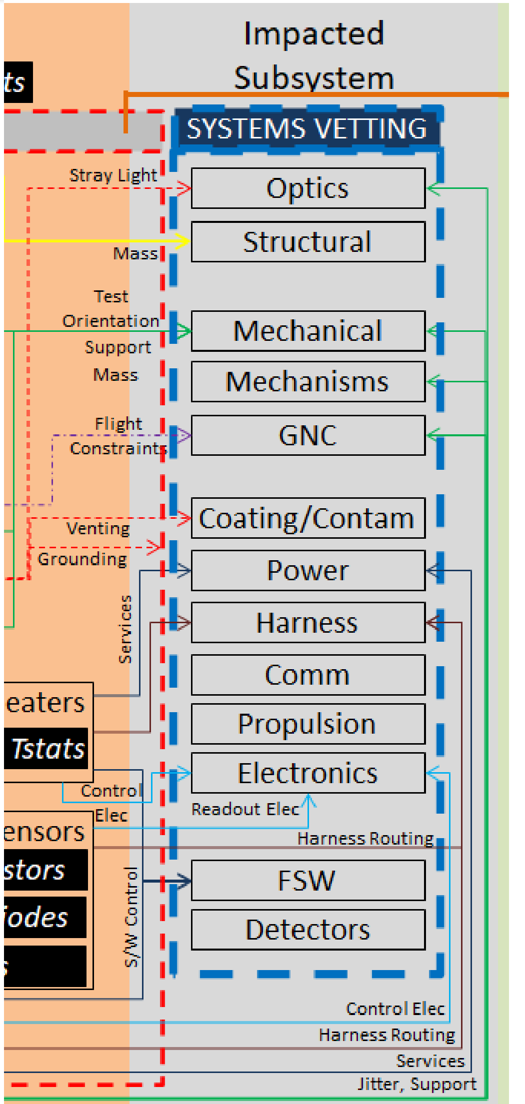


Thermal Design Process Flow



You have a design, but what do you need from others to implement it?

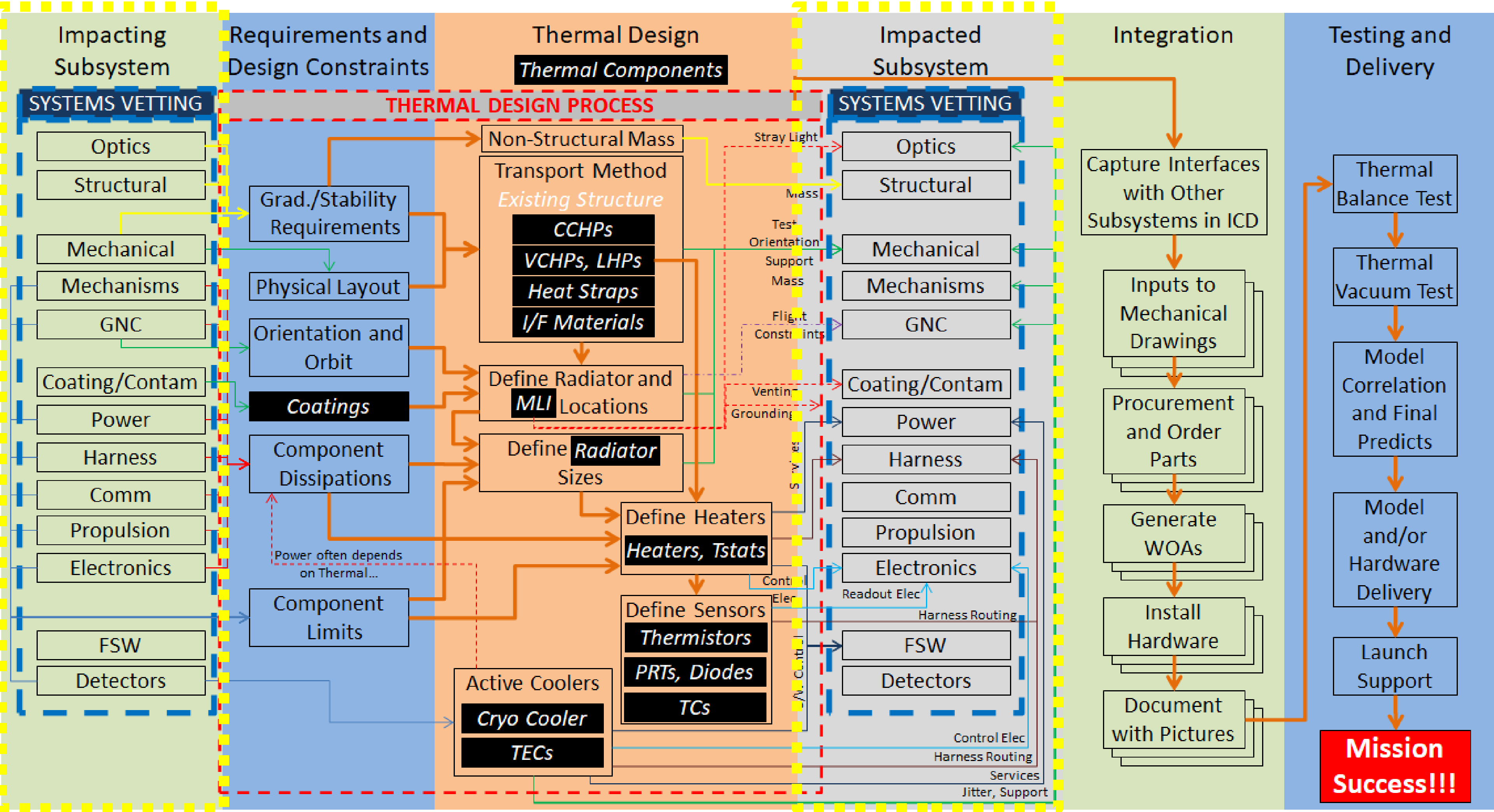
- ***Thermal Designs are never detached from the rest of the system***
  - *Radiators: may require mechanical support and may impose flight constraints*
  - *Thermal Mass for Stability: may require stronger mechanical support*
  - *Heatpipes: require mechanical support and may impose test levelness requirements*
  - *Blankets: require grounding, venting, and may need further work for stray light concerns*
  - *Heaters: will require harness, power services, and possibly flight software for control*
  - *Thermostats: will require harness*
  - *Sensors: will require harness, and flight software read out capability*
  - *Coolers: will require harness, power services, and flight software control, may require jitter isolation*



Accommodating the Thermal Design

- ***Harness***
  - *Harness routing and wire definitions are needed for all sensors, heaters, and any other thermal components needing power/readout*
- ***Power Services***
  - *A limited number of switches/relays are available*
  - *Circuits can carry a limited number of amps*
- ***Flight Software***
  - *A limited number of channels are available to be read by the avionics and be stored in the housekeeping telemetry stream*
  - *Control algorithms for heaters/coolers may require additional lines of code*
- ***Mechanical Support***
  - *Additional mass and design work may be needed to support radiators (brackets)*
- ***Flight Constraints***
  - *Sun or other source avoidance may need to be accounted for by ACS/GNC*
- ***Test Constraints***
  - *Testing orientation may be difficult to accommodate given other GSE needs (targets, stimulators, cryo and heater panels, chamber availability)*
- ***Documentation***
  - *Drawings need to be done for hardware locations, electrical schematics, coating masking*
  - *Work Order Authorizations need to be generated for the installation of thermal hardware*

Working with Systems Engineering



Working with Systems Engineering

- ***In the Thermal Design process, Systems Engineering wraps around all disciplines***
  - *At times what is best for one subsystem is detrimental to another*
  - *It is the Systems Engineering Teams job to determine the optimum*
  - *Thermal interfaces closely with Systems, both on incoming/outgoing design parameters*
- ***Most often, Systems keeps a Master Equipment List (MEL) which captures all the hardware necessary for the design and includes mass, Technology Readiness Level (TRL), redundancy, Temperature Limits, etc. Thermal provides inputs to the MEL in terms of the mass of the thermal hardware to implement into the design***
- ***As a corollary, Systems also keeps a Power Equipment List (PEL), which serves as the bookkeeping for all power used by the system. For thermal, this is an excellent source for the dissipations for the various components, both Current Best Estimates (CBE) and Maximum Expected Value (MEV) or Allocations***
- ***As projects mature, updates to the MEL and PEL must be vetted and tracked to ensure that no changes have a significant impact on the design (e.g. power growth leading to a larger radiator)***

Resource Budgets

- ***For a given project, there are finite resources that are tracked throughout the project life cycle, including:***
  - Mass
  - Power
  - Cost
  - Time (expressed as Schedule)
- ***The thermal engineer is responsible for keeping their contributions to these budgets up to date***
  - This includes regular updates to Mass and Power as the design evolves throughout the project life cycle (especially the heater power demands)
  - It also includes the procurement of the necessary hardware to meet the cost budget constraints and the overall Integration and Test (I&T) flow for the project
  - Many of the smaller thermal components, such as heaters, sensors, and thermostats are off the shelf products and have their own IEEE specifications
  - Other, more complex thermal hardware (such as HeatPipes, CryoCoolers, Radiator Panels) will need to have their specifications generated and go out for competitive procurement

Where does Thermal Analysis Fit In?

- ***Once a design concept has been formulated, thermal analysis of the design is performed to ensure requirements are met***
  - The generally accepted practice is to stack all worst case hot and cold parameters and ensure the predictions are within limits with margin
- ***The updates and data that feed into the budgets are typically derived from this detailed thermal analysis of the system***
  - A presentation on Thermal Analysis can be found at ntrs.nasa.gov under the title "Thermal Modeling and Analysis"
- ***Some foundations should first be discussed that are not design/project specific…***
  - Design Margin Philosophy: GSFC typically maintains 5°C of margin to limits or for components under heater control utilizes no more than 70% of heater capacity. Greater margins may be needed for cryogenic applications. Other organizations may have different margin philosophies…
  - Power Growth Allowance: if power dissipation Allocations (or Maximum Expected Values [MEV] or Not To Exceed [NTE] values) are not specified, it is advisable to include a factor for power growth allowance beyond a Current Best Estimate [CBE]. Until measured values are available (usually late in a program), 30% uncertainty is not unreasonable
  - Material Properties: Thermophysical properties should have traceability to their source and not just be what was used on the last project
  - Thermo-Optical Properties: Thermo-optical properties should consider the range of possible values for a mission based on measurement uncertainty as well as expected degradation due to the space environment

Wrap Up

- ***The thermal design process is well established***
  - It begins with gathering requirements
  - The thermal engineer then specifies the thermal design including components to meet requirements as well as resources needed for implementation
  - Analysis is performed to validate the design and once an accepted level of maturity is reached at critical project milestones, the proposed hardware is procured
  - The hardware is then installed during the integration and test phase
  - After the hardware installations are completed, the article is put through rigorous testing to ensure performance and that all requirements are met
  - The thermal model is correlated to the test data to provide the most accurate predictions for flight
  - The hardware is then delivered to the next higher level of assembly (e.g. instrument, spacecraft, launch vehicle)
- ***Once in flight, the thermal telemetry is monitored during commissioning to ensure performance is within expected parameters***
  - Resources permitting, a correlation to flight data may also be performed

Other Resources

- GOLD Rules: GSFC-STD-1000G
- GEVS: GSFC-STD-7000B
- (GSFC Internal) ETD Wiki: https://spaces.gsfc.nasa.gov/display/CODE545/545+Home
- (GSFC Internal) Orbit Calculator (Excel spreadsheet), David Everett, dtd 2/27/2017
- Spacecraft Thermal Control Handbook , The Aerospace Corporation, David Gilmore Editor, 2002
  - Vol 1: Fundamental Technologies
  - Vol 2: Cryogenics
- Satellite Thermal Control for Systems Engineers
  Robert Karam Progress in Astronautics and Aeronautics Series, V-181 Published by AIAA, © 1998
- Radiant-Interchange Configuration Factors, National Advisory Committee for Aeronautics, December 1952.
- Thermodynamics of Space Flight (Heat Transfer Phenomena in Space), NASA GSFC, M. Schach and R. Kidwell, Jr., March 1963.

Other Resources - continued

Hardware:

- S-311-P-079, “PROCUREMENT SPECIFICATION FOR THERMOFOIL HEATER”
- S-311-P-18, “THERMISTOR, (THERMALLY SENSITIVE RESISTOR), INSULATED AND UNINSULATED, NEGATIVE TEMPERATURE COEFFICIENT, SPECIFICATION“
- S-313-013, “ADHESIVE BONDING OF PLATINUM RESISTANCE TEMPERATURE SENSORS TO SUBSTRATE SURFACES”
- S-311-641, “SWITCHES, THERMOSTATIC, GENERAL REQUIREMENTS FOR”
- S-311-641/02, “SWITCH, THERMOSTATIC, BIMETALLIC, SPST, NARROW DIFFERENTIAL, HERMETIC, DETAIL SPECIFICATION FOR”
- “MECHANICALLY PUMPED FLUID LOOPS FOR SPACECRAFT THERMAL CONTROL: PAST, PRESENT & FUTURE”, P. BHANDARI, TFAWS 2004
- HEAT PIPE DESIGN HANDBOOK, VOLS 1 & 2, JUNE 1979 (B&K ENGINEERING FOR NASA GSFC
- CHI S. W., HEAT PIPE THEORY AND PRACTICE: A SOURCEBOOK, 1976
- REAY D. A., HEAT PIPES: THEORY, DESIGN AND APPLICATIONS, 2014
- KARAM R. D., SATELLITE THERMAL CONTROL FOR SYSTEMS ENGINEERS, 1998
- FAGHRI A. HEAT PIPE SCIENCE AND TECHNOLOGY, 2ND EDITION, 2016
- ZOHURI B. HEAT PIPE DESIGN AND TECHNOLOGY: MODERN APPLICATIONS FOR PRACTICAL THERMAL MANAGEMENT, 2ND EDITION, 2016

Installation/Fabrication Processes:

- S-313-022/541-SPEC-022 ADHESIVE BONDING KAPTON THERMOFOIL HEATERS TO SUBSTRATE SURFACES
- S-313-014/541-SPEC-014, “ADHESIVE BONDING OF THERMISTOR SENSORS TO SUBSTRATE SURFACES”
- 545-WI-8072.1.8, “PROCEDURE FOR VERIFICATION OF THERMOSTAT OPERATION”
- 546-WI-8072.1.74 PROCEDURE FOR APPLICATION OF TRANSFER ADHESIVES FOR TAPE FABRICATION, THERMAL BLANKET PRODUCTION, AND HEATER ATTACHMENTS
- 541-WI-8072.1.26, “PROCESSES FOR THE ADHESIVE BONDING OF THERMAL CONTROL COMPONENTS ON FLIGHT HARDWARE”

Thermal Insulation:

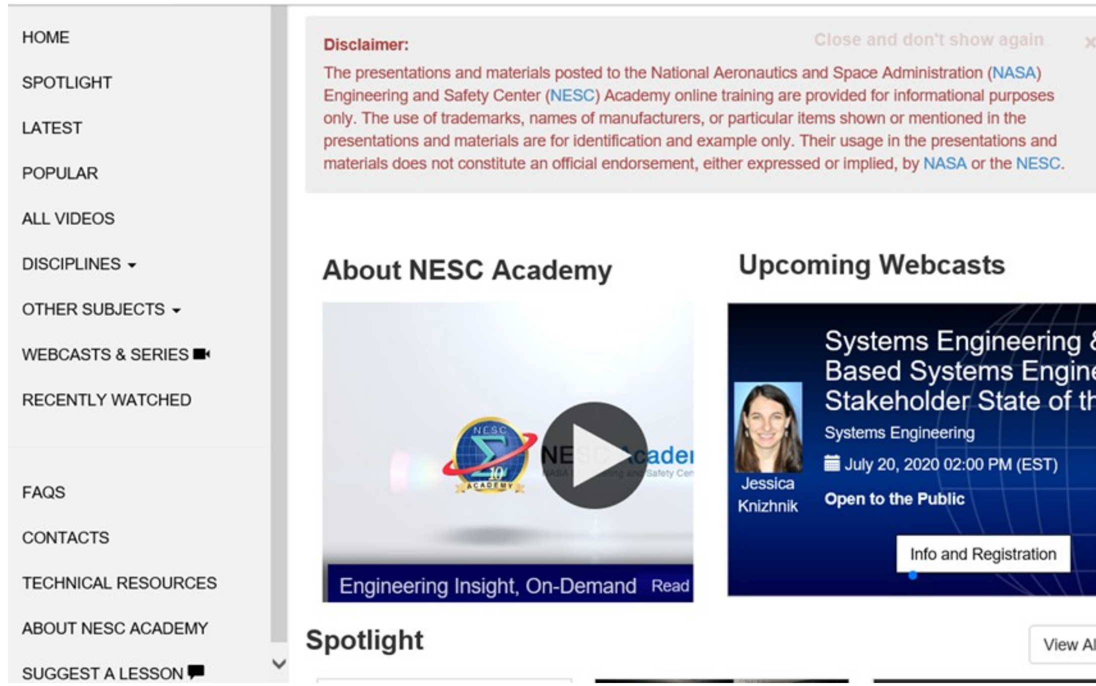
- NASA/CR-72747, “FINAL REPORT – THERMAL PERFORMANCE OF MULTI-LAYER INSULATIONS”, J. BARBER (LeRC), APRIL 20TH, 1971
- NASA/CR-134477, “FINAL REPORT – THERMAL PERFORMANCE OF MULTI-LAYER INSULATIONS”, W. JOHNSON (MSFC), APRIL 5TH, 1974
- NASA/TP-1999-209263, “MULTI-LAYER INSULATION MATERIAL GUIDELINES”, M. FINCKENOR (MSFC)
- 549-WI-8072.0.2, “DESIGN AND FABRICATION OF THERMAL BLANKETS”, NASA GSFC/549

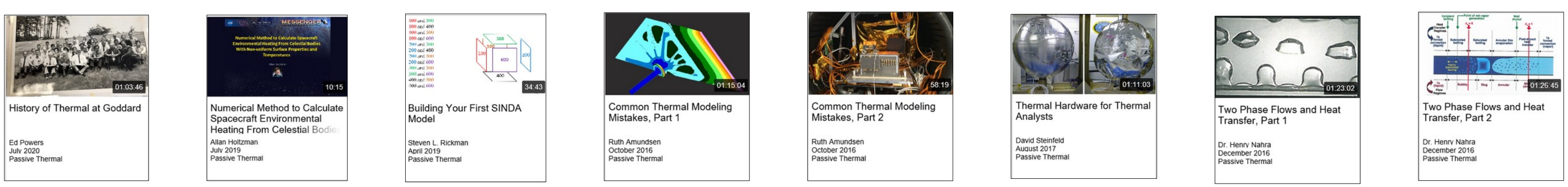
Other Resources – NESC Academy

- Organized kinda like Netflix
  - Subsystems: Passive Thermal

https://nescacademy.nasa.gov

➢ Numerous videos on thermal design





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- "Spacecraft Thermal Control Handbook", David Gilmore, 2002
- "Space Mission Analysis and Design", Wiley & Larsen, 3rd edition, 5th printing 2003
- "Thermal Radiation Heat Transfer", Siegel & Howell
- General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems, and Components
  - http://arioch.gsfc.nasa.gov/302/gevs-se/toc.htm
- "Test Requirements for Launch, Upper-Stage, and Space Vehicles", MIL-STD-1540

Acronyms

General Terms | Analysis Terms | Hardware Terms

- NASA: National Aeronautics and Space Administration
- GSFC: Goddard Space Flight Center
- PDR: Preliminary Design Review
- CDR: Critical Design Review
- PSR: Pre-Ship Review
- GNC: Guidance, Navigation, and Control
- FSW: Flight Software
- Comm: Communications
- QA: Quality Assurance
- CAD: Computer Aided Design
- EMI/EMC: Electro Magnetic Interference/Compatibility
- GEVS: General Environment Verification Specifications
- GMM: Geometric Math Model
- TMM: Thermal Math Model
- Q_{ij}: heat flow from i to j
- T_i: temperature for i
- A_x: cross sectional area
- L: length
- k: thermal conductivity
- mCp: Mass times Specific Heat
- σ: Stefan Boltzman Constant
- A_i: surface area for i
- Radk: Radiation coupling
- B_{ij}: Interchange Factor
- F_{ij}: View Factor
- α: banded UV absorptivity
- ε: banded IR absorptivity/emissivity

- TB: Thermal Balance
- TV: Thermal Vacuum
- GSE: Ground Support Equipment
- ICD: Interface Control Document
- EEE: Electrical, Electronic, and Electromechanical
- WOA: Work Order Authorization
- I&T: Integration and Test
- IR: Infrared
- UV: Ultraviolet
- BOL: Beginning of Life
- EOL: End of Life
- MLI: Multi Layer Insulation
- CCHP: Constant Conductance Heat Pipe
- VCHP: Variable Conductance Heat Pipe
- NCG: Non-Condensable Gas
- LHP: Loop Heat Pipe
- I/F: Interface
- MLI: Multi Layer Insulation
- OSR: Optical Surface Reflector
- RTD: Resistance Temperature Device
- PRT: Platinum Resistance Thermometer
- TC: Thermocouple
- TEC: Thermo Electric Cooler
- PCM: Phase Change Material
- APG: Annealed Pyrolytic Graphite
- PSA: Pressure Sensitive Adhesive
- VDA: Vapor Deposited Aluminum

More Acronyms

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
α	Solar Absorptance
Alt	Altitude
ASSY	Assembly
Bij	Interchange Factor
BOL	Beginning of Life
CAD	Computer Aided Design
Cp	Specific Heat
DT	Temperature Difference
ε	Infrared Emissivity
ε*	Effective Emissivity
EOL	End of Life
FD	Finite Difference
FE	Finite Elements
GOLD	Goddard Open Learning Design
GSFC	Goddard Space Flight Center
h_{cond}/h_{evap}	Condenser / Evaporator Heat Transfer Coefficient
HP	Heat Pipe
HR	Heat Rate
ID	Identifier
IF	Interface
Incl	Inclination
IR	Infra Red
k	Thermal Conductivity
MCRT	Monte Carlo Ray Trace
MLI	Multi-Layer Insulation
NCG	Non-Condensable Gas
PCM	Phase Change Material
PID	Proportional-Integral-Derivative
ρ	Density
RAAN	Right Ascension of Ascending Node
Radk	Radiation coupling
RES	Reservoir
SC	Spacecraft
SINDA	Systems Improved Numerical Difference Analyzer
STEP	Standard for the Exchange of Product Model Data
STOP	Structural-Thermal-Optical-Performance
TD	Thermal Desktop
TEC	Thermo Electric Cooler
UV	Ultraviolet-Visible
VCHP	Variable Conductance Heat Pipe
VP	View Port