Mysteries of Heat Transfer in Space

(Mainly satellites in near vacuum)

Radiation equation

- Heat transfer by thermal radiation between 2 bodies:

$$Q = A_{12} * \mathcal{F}_{12} * \sigma *(T_1^4 - T_2^4)$$

$\mathcal{F}$, called “Script F”, function of surface property and geometry

Temperature in absolute units (e.g. Kelvin)

The **Stefan–Boltzmann constant** (also **Stefan's constant**), a physical constant denoted by the Greek letter σ (sigma), is the constant of proportionality in the Stefan–Boltzmann law: "the total intensity radiated over all wavelengths increases as the temperature increases", of a black body which is proportional to the fourth power of the thermodynamic temperature

from Wikipedia

The value of the Stefan–Boltzmann constant is given in SI units by

$$\sigma = 5.670\,367(13) \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}.$$ [5]

In cgs units the Stefan–Boltzmann constant is:

$$\sigma \approx 5.6704 \times 10^{-5}\ \mathrm{erg \cdot cm^{-2} \cdot s^{-1} \cdot K^{-4}}.$$

In thermochemistry the Stefan–Boltzmann constant is often expressed in $\mathrm{cal \cdot cm^{-2} \cdot day^{-1} \cdot K^{-4}}$:

$$\sigma \approx 11.7 \times 10^{-8}\ \mathrm{cal\ cm^{-2} \cdot day^{-1} \cdot K^{-4}}.$$

In US customary units the Stefan–Boltzmann constant is:[6]

$$\sigma \approx 1.714 \times 10^{-9}\ \mathrm{BTU \cdot hr^{-1} \cdot ft^{-2} \cdot {}^{\circ}R^{-4}}.$$

Environmental loads

- **Solar:**
  - The **solar constant** (***G**SC*) is a flux density measuring mean solar electromagnetic radiation (solar irradiance) per unit area. It is measured on a surface perpendicular to the rays, one astronomical unit (AU) from the Sun (roughly the distance from the Sun to the Earth).
  - Solar irradiance is measured by satellites above Earth's atmosphere,[3] and is then adjusted using the inverse square law to infer the magnitude of solar irradiance at one Astronomical Unit (AU) to evaluate the solar constant.[4] The approximate average value cited,[1] 1.3608 ± 0.0005 kW/m^2, which is 81.65 kJ/m^2 per minute, is equivalent to approximately 1.951 calories per minute per square centimeter, or 1.951 langleys per minute. Solar output is nearly, but not quite, constant.
  - 1360.9 ± 0.5 W/m (2011)
  - The solar constant includes all wavelengths of solar electromagnetic radiation, not just the visible light (see Electromagnetic spectrum). It is positively correlated with the apparent magnitude of the Sun which is −26.8. The solar constant and the magnitude of the Sun are two methods of describing the apparent brightness of the Sun, though the magnitude is based on the Sun's visual output only.
- Albedo

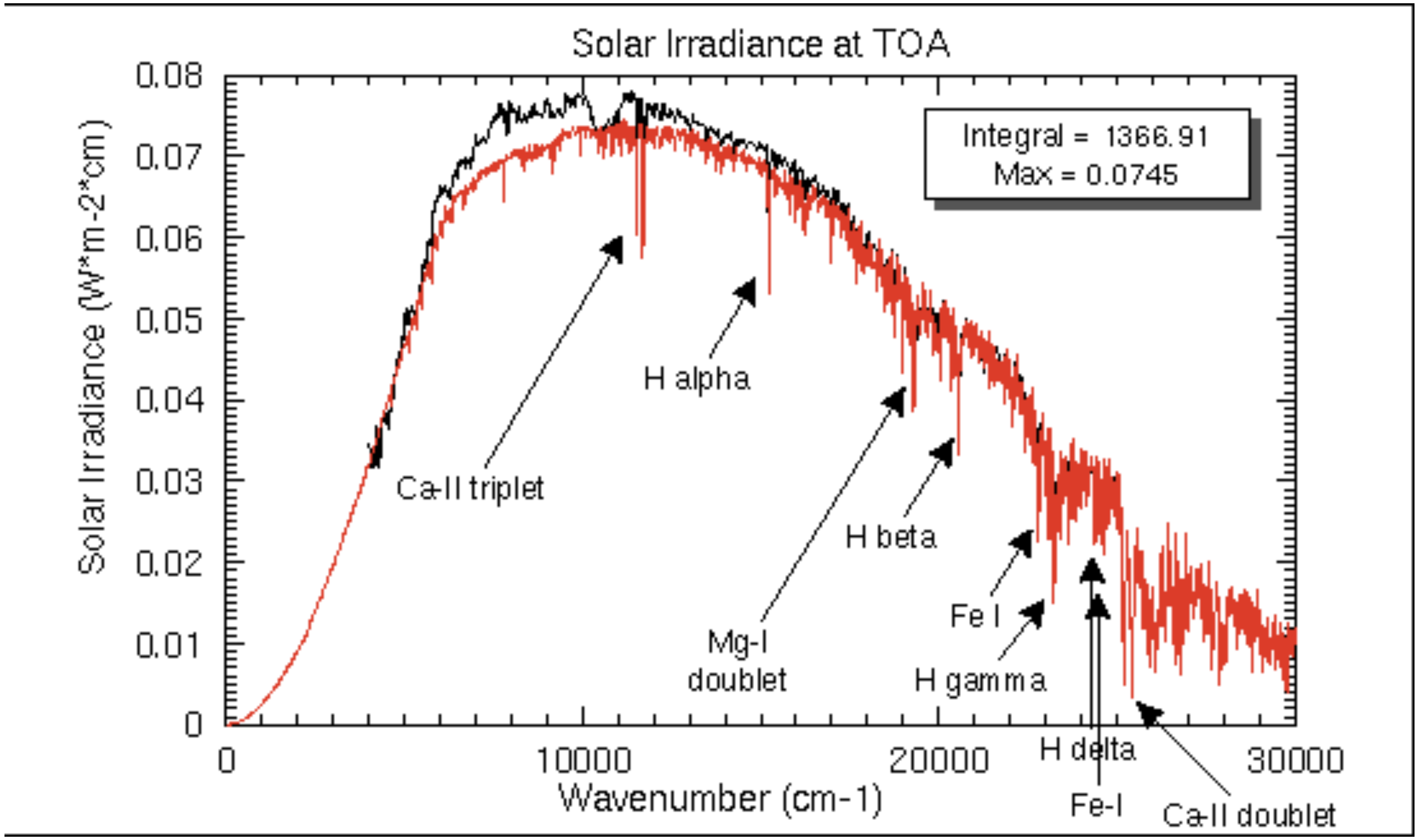
  average of 0.3
- Earth IR

  https://ttu-ir.tdl.org/bitstream/handle/2346/72957/ICES_2017_142.pdf?sequence=1&isAllowed=y

Solar constant

The solar constant includes all types of solar radiation, not just the visible light. It is measured by satellite as being 1.361 kilowatts per square meter (kW/m²) at solar minimum and approximately 0.1% greater (roughly 1.362 kW/m²) at solar maximum

Wikipedia



Earth temperature

Table 3: Average measured Earth black body temperature over 5 years depending on the latitude and depending on the season based on 5 years of CERES Earth IR measurement (2007-2011) (values in K)

Average Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Ave. over 2007*	*Ave. over 2008*	*Ave. over 2009*	*Ave. over 2010*	*Ave. over 2011*	Average over 5-year
85°	233	236	235	241	247	251	252	250	245	240	236	234	*242*	*242*	*242*	*242*	*242*	**242**
75°	235	236	237	242	248	251	253	251	247	242	238	236	*243*	*243*	*243*	*244*	*243*	**243**
65°	237	238	241	245	249	253	254	252	249	244	240	237	*245*	*245*	*245*	*245*	*245*	**245**
55°	241	242	244	248	251	253	255	254	251	248	244	242	*248*	*248*	*248*	*248*	*248*	**248**
45°	245	246	247	250	253	256	258	259	257	252	249	246	*252*	*252*	*251*	*251*	*252*	**252**
35°	251	251	253	254	257	259	262	262	261	258	255	252	*257*	*257*	*256*	*256*	*256*	**256**
25°	261	261	262	262	262	262	262	262	262	263	262	261	*262*	*262*	*262*	*262*	*262*	**262**
15°	264	265	265	263	261	258	256	255	256	259	261	263	*261*	*261*	*261*	*261*	*260*	**261**
5°	258	259	258	255	254	254	254	255	255	255	256	257	*256*	*255*	*256*	*256*	*256*	**256**
-5°	255	255	255	256	259	261	261	262	261	260	258	257	*258*	*258*	*258*	*258*	*259*	**258**
-15°	257	257	259	262	264	265	265	266	265	263	260	258	*262*	*262*	*262*	*262*	*262*	**262**
-25°	261	262	262	261	261	260	262	262	262	261	260	260	*261*	*261*	*261*	*261*	*261*	**261**
-35°	260	260	259	257	255	254	254	255	255	256	256	258	*257*	*256*	*256*	*257*	*257*	**257**
-45°	254	254	253	251	250	249	248	249	249	251	252	253	*251*	*251*	*251*	*251*	*251*	**251**
-55°	249	249	248	246	245	244	243	243	244	246	247	249	*246*	*246*	*246*	*246*	*246*	**246**
-65°	247	246	244	241	239	237	237	236	238	241	244	246	*242*	*241*	*242*	*241*	*241*	**241**
-75°	244	240	235	230	228	225	224	224	226	231	238	243	*233*	*232*	*233*	*232*	*233*	**233**
-85°	242	236	229	224	222	219	218	216	219	226	235	242	*228*	*228*	*228*	*228*	*228*	**228**
Average	**254**	**254**	**254**	**254**	**255**	**255**	**256**	**256**	**255**	**255**	**254**	**254**	*255*	*255*	*255*	*255*	*255*	**255**

Using real Earth Albedo and Earth IR Flux for Spacecraft Thermal Analysis
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ESA, ESTEC, Noordwijk, The Netherlands, ICES-2017-142
47th International Conference on Environmental Systems ICES-2017-142 16-20 July 2017, Charleston, South Carolina

Net Solar loads

$Q_s = \alpha_{uv} * A_p * S$

where

α_{uv} = absorptivity in the UV spectrum

A_p = projected area

S = solar constant

$Q_r = \epsilon_{IR} * F * A * \sigma * T^4$

where

ϵ_{IIR} = emissivity in the IR spectrum

Since in equilibrium $Q_s = Q_r$, we can solve for T:

$T = ((\alpha_{uv} * A_p * S)/(\epsilon_{IR} * F * A * \sigma))^{1/4}$

Note parameter $\alpha_{uv}/\epsilon_{IR}$

Material	Emissivity
Aluminum foil	0.03
Aluminum, anodized	0.9[12]
Asphalt	0.88
Brick	0.90
Concrete, rough	0.91
Copper, polished	0.04
Copper, oxidized	0.87
Glass, smooth (uncoated)	0.95
Ice	0.97
Limestone	0.92
Marble (polished)	0.89 to 0.92
Paint (including white)	0.9
Paper, roofing or white	0.88 to 0.86
Plaster, rough	0.89
Silver, polished	0.02
Silver, oxidized	0.04
Snow	0.8 to 0.9
Transition metal Disilicides (e.g. $MoSi_2$ or WSi_2)	0.86 to 0.93
Water, pure	0.96

Wikipedia

http://matthewwturner.com/uah/IPT2008_summer/baselines/LOW%20Files/Thermal/Spacecraft%20Thermal%20Control%20Handbook/04.pdf

4 Thermal Surface Finishes

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Table 4.1. Properties of Common Thermal Surface Finishes

Surface Finish	α—Absorptance (beginning-of-life)	ε—Emittance
Optical Solar Reflectors		
8-mil quartz mirrors	0.05 to 0.08	0.80
Quartz mirrors (diffuse)	0.11	0.80
2-mil silvered Teflon	0.05 to 0.09	0.66
5-mil silvered Teflon	0.05 to 0.09	0.78
2-mil aluminized Teflon	0.10 to 0.16	0.66
5-mil aluminized Teflon	0.10 to 0.16	0.78

White Paints		
S13G-LO	0.20 to 0.25	0.85
PCBZ	0.16 to 0.24	0.87
Z93	0.17 to 0.20	0.92
ZOT	0.18 to 0.20	0.91
Chemglaze A276	0.22 to 0.28	0.88
Black Paints		
Chemglaze Z306	0.92 to 0.98	0.89
3M Black Velvet	~0.97	0.84
Aluminized Kapton		
1/2 mil	0.34	0.55
1 mil	0.38	0.67

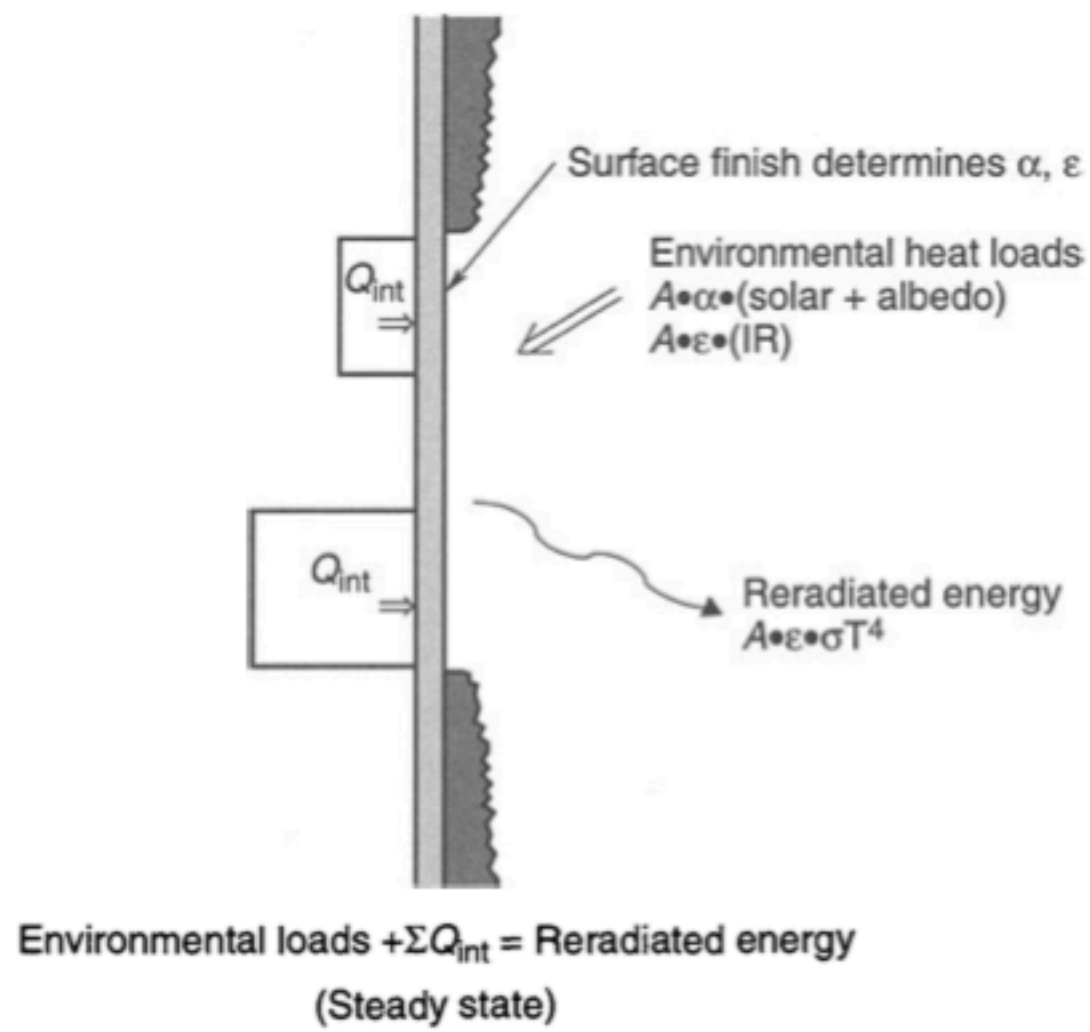


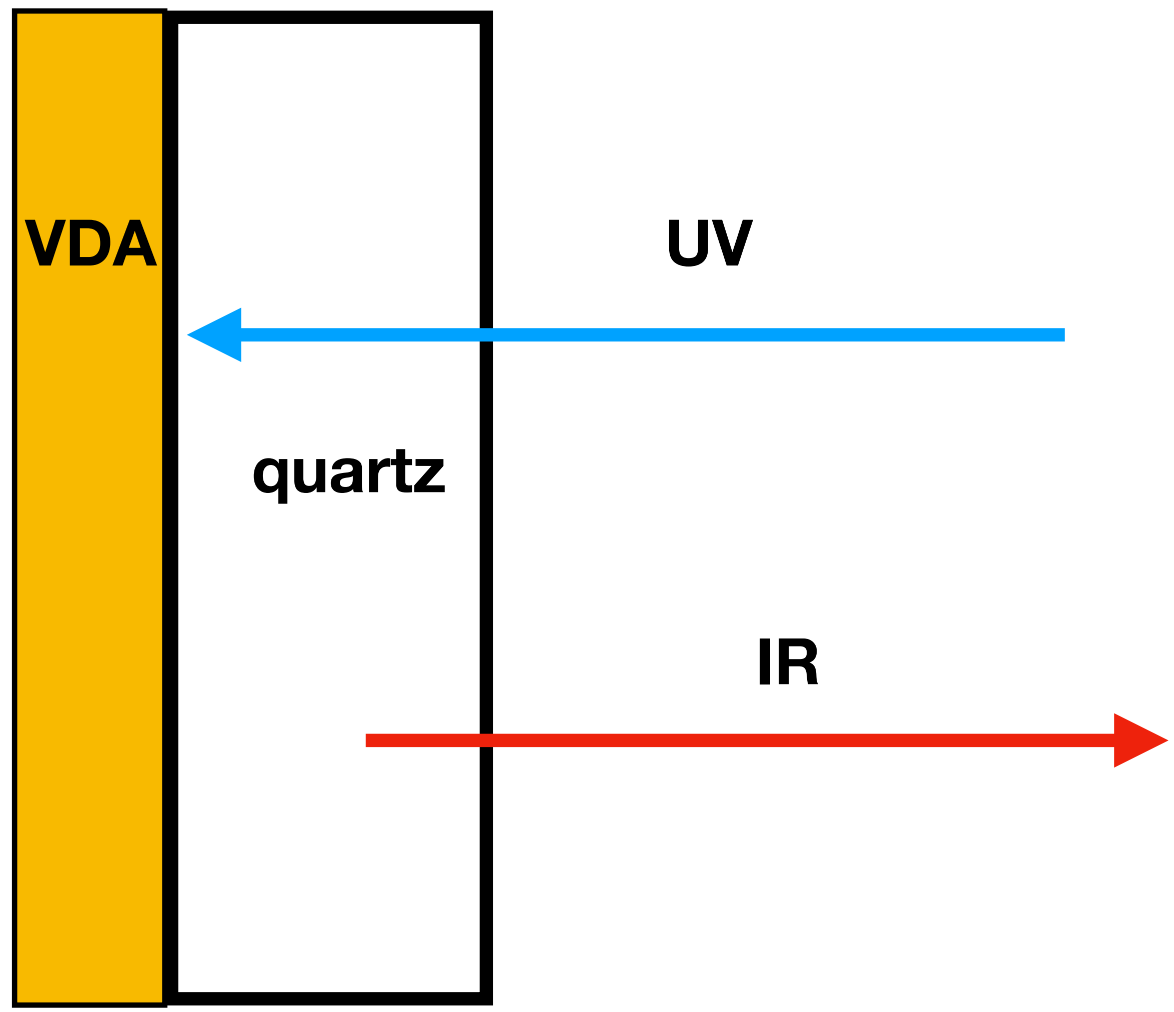
Fig. 4.1. Radiator energy balance (no external blockage).

Thermal radiator mirror

$$Q = \mathrm{Sol} \times A_{proj} \times \alpha_{uv} = A \times \mathscr{F} \times \sigma \times T^4$$

$\mathscr{F} = \epsilon_{IR}$ in degenerate case

UV passes through quartz, reflected by VDA. What isn't reflected, is absorbed as heat , transferred to quartz and emitted as IR energy



Sol = solar constant

σ = Stefan – Boltzmann const

Kirchhoff's law: $\alpha_\lambda = \epsilon_\lambda$

Flat plate equilibrium temperatures

sigma	solar const	alpha	emiss	Rankine
1.73E-09	450	0.9	0.85	264.431787551243
1.73E-09	450	0.21	0.8	51.1800894030152
1.73E-09	450	0.9	0.85	264.431787551243
1.73E-09	450	0.4	0.85	131.496077650951
1.73E-09	450	0.2	0.05	549.965643661738

α / ϵ ratio controls the temperature

Take aways

- α **usually correlates to visual appearance.**
- **Shiny surfaces have low values, dark surfaces have high.**
- **Usually only important on external surfaces.**
- **Low value surfaces are prone to contamination**

- ϵ **does not correlate to visual appearance.**
    - **e.g., black and white paint have nearly the same value.**
- **High emissivity surfaces can be poor conductors**
    - **can lead to charge build up on external surfaces.**

Cryogenics is tough

- **T^4 law makes it very hard to reject heat at low temperatures**
- **Parasitics can kill designs**
  - **Heat leaks that are negligible at room temperature dominate at low temperature**
- **Passive cryo radiators can become very large**
  - **Cryo radiators can severely restrict vehicle attitude**
  - **Cryo coolers are a good idea if you know how to build them**
- **Surface properties can be very different at cryogenic temperatures**
- **Cryogenic thermal hardware can be very fragile**

Conduction Heat Transfer

- Simple linear equation for steady state one dimensional heat transfer in a homogeneous medium:

$$Q = k\ A\ \Delta T/L,\ k = \text{thermal conductivity}$$

- For interfaces:

$$Q = h\ A\ \Delta T,\ h = \text{interface coefficient that came from proprietary place}$$

  - Vacuum between “dry” interfaces greatly reduces heat transfer
  - “Wet” interfaces (e.g. RTV, epoxy) can be very unpredictable

Heatpipes

From Wikipedia, the free encyclopedia

A **heat pipe** is a heat-transfer device that combines the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces.[citation needed]

At the hot interface of a heat pipe a liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing heat from that surface. The vapor then travels along the heat pipe to the cold interface and condenses back into a liquid – releasing the latent heat. The liquid then returns to the hot interface through either capillary action, centrifugal force, or gravity, and the cycle repeats. Due to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors. The effective thermal conductivity varies with heat pipe length, and can approach 100 kW/(m·K) for long heat pipes, in comparison with approximately 0.4 kW/(m·K) for copper.[citation needed]

- Constant conduction heatpipes are usually grooved (the wick) aluminum extrusions with ammonia as the working fluid for room temperature applications.

- Cryo heatpipes use different working fluids

- Variable conduction heatpipes are two heatpipes working against each other, these days with one side controlled by a heater feedback loop

Multi layer insulation

From Wikipedia, the free encyclopedia

Multi-layer insulation, or **MLI**, is thermal insulation composed of multiple layers of thin sheets and is often used on spacecraft. It is one of the main items of the spacecraft thermal design, primarily intended to reduce heat loss by thermal radiation. In its basic form, it does not appreciably insulate against other thermal losses such as heat conduction or convection. It is therefore commonly used on satellites and other applications in vacuum where conduction and convection are much less significant and radiation dominates. MLI gives many satellites and other space probes the appearance of being covered with gold foil.

- VDA deposited on usually Kapton or Mylar sheets