MEEG346 Thermal Laboratory

Experiments X-5

Objective: Compare Modes of Heat Transfer:

- Free Convection
- Forced Convection
- Radiation Heat Transfer

MEEG346 Thermal Laboratory

Laboratory Problem X-5 – Forced Convection and Radiation Heat Transfer

You are, or will be, working on these modes of heat transfer in class.

This lab is intended to provide some hands on experience with them.

The Forced Convection lab apparatus has all three working simultaneously.

Which one dominates when?

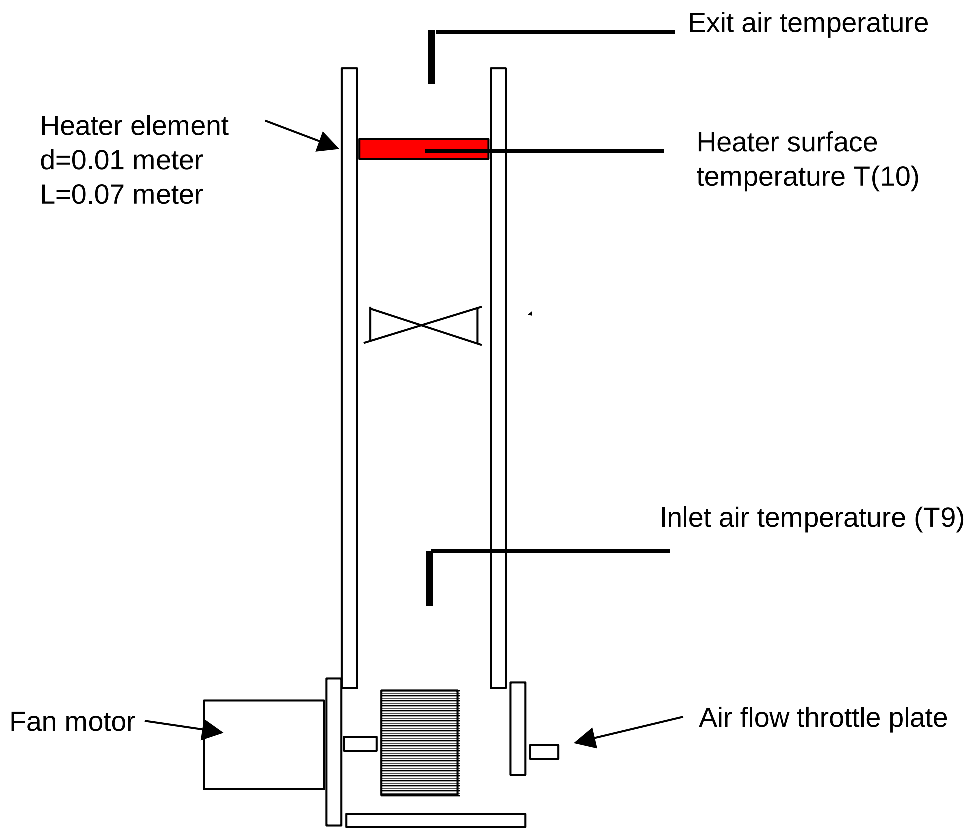
Forced convection is a situation where a fluid is forced (by pump or fan) over a surface and exchanges heat..

Natural Convection is a where the fluid flow results from its being heated by a solid surface. “Hot air rises”.

Radiant Heat Transfer is transmitted by microwaves radiation from a hot surface to a cooler surface.

In analysis, one often makes an informed judgment to only consider the dominant mechanism.

We will compare all three in this experiment.



Fan off: Natural convection from the heater element.
Fan on: Forced convection from the heater element.
Radiation is present in both cases. It may or may not be significant.

In this lab, we will use standard correlations for the convective heat transfer coefficients rather than measure them. We will use the radiation heat transfer equation , initially assuming F=1.

The sum of (convection + radiation) <u>should</u> equal the measured power input.

9.6.3 The Long Horizontal Cylinder

From textbook, pp. 581-582.

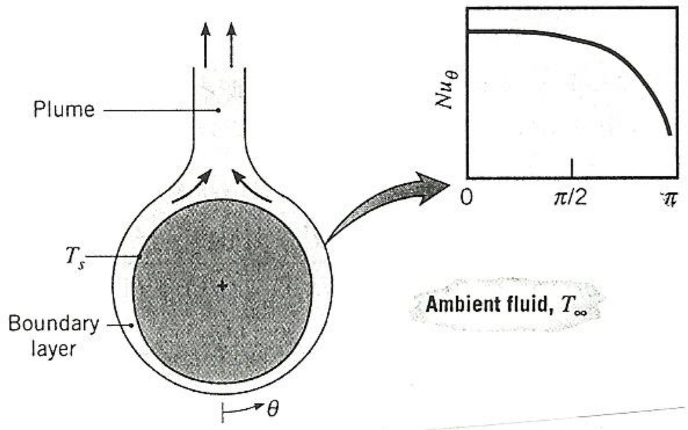
$$\overline{Nu}_D = \frac{\bar{h}D}{k} = C\,Ra_D^n \qquad (9.33)$$

Nu = hD/k

h_{nc} = Nu*k/D

TABLE 9.1 Constants of Equation 9.33 for free convection on a horizontal circular cylinder [20]

Ra_D	C	n
10^{-10}–10^{-2}	0.675	0.058
10^{-2}–10^{2}	1.02	0.148
10^{2}–10^{4}	0.850	0.188
10^{4}–10^{7}	0.480	0.250
10^{7}–10^{12}	0.125	0.333



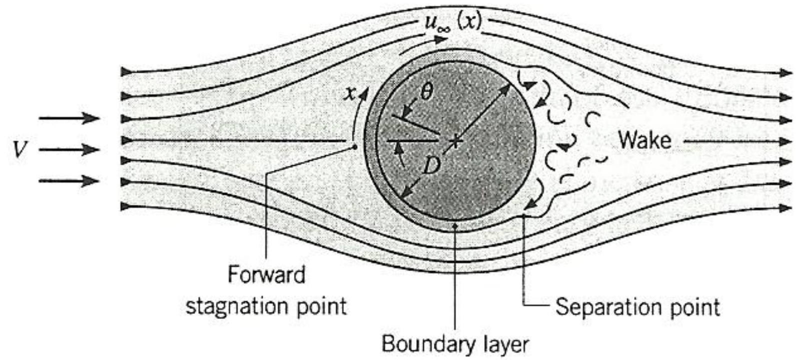


FIGURE 7.5 Boundary layer formation and separation on a circular cylinder in cross flow.

$\overline{Nu}_D = C\, Re_D^m\, Pr^{1/3}$ (Table 7.2)	(7.52)	Cylinder	Average, T_f, $0.4 \lesssim Re_D \lesssim 4 \times 10^5$, $Pr \gtrsim 0.7$
$\overline{Nu}_D = C\, Re_D^m\, Pr^n (Pr/Pr_s)^{1/4}$ (Table 7.4)	(7.53)	Cylinder	Average, T_∞, $1 \lesssim Re_D \lesssim 10^6$, $0.7 \lesssim Pr \lesssim 500$
$\overline{Nu}_D = 0.3 + [0.62 Re_D^{1/2}\, Pr^{1/3} \times [1 + (0.4/Pr)^{2/3}]^{-1/4}] \times [1 + (Re_D/282{,}000)^{5/8}]^{4/5}$	(7.54)	Cylinder	Average, T_f, $Re_D\, Pr \gtrsim 0.2$

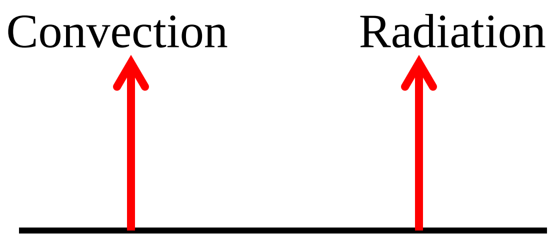
Textbook, Table 7.7, pg 463.
Three choices for cylinders, depending on Reynolds and Prandtl numbers.

Radiation heat transfer has an entirely different physics from conduction and convection heat transfer. It is at once fascinating and complex.

•As a heat transfer mechanism, most of the action involves the infrared wavelengths of the electromagnetic spectrum.

• (It's what sun-burns you at the beach)

•Radiation from a hot surface occurs independently of either natural or forced convection from the same surface.



Radiation essentials:

$$q_{rad} = \varepsilon\,\sigma\,F\,(\,T_s{}^4 - T_{sur}{}^4\,) \quad \text{w/m^2}$$

ε = surface emissivity (0< ε < 1, dimensionless)
σ = Stefan-Boltzmann constant = $5.67\text{x}10^{-8}$ W/m^2-K
F= shape or configuration factor (0<F<1, dimensionless)
T_s = Hot surface temperature, ^{o}K.
T_{surr} = Temperature of surroundings, ^{o}K always

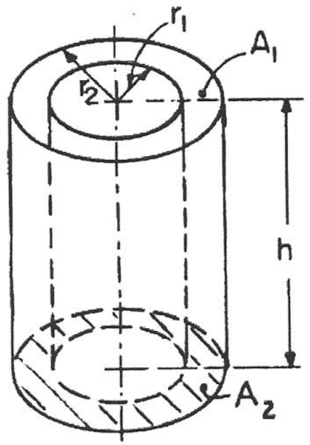
Slide-ruler's simplification:

Multiply and divide the RHS by 10^8. Rearrange and get

$$q_{rad} = 5.67\,\varepsilon\,F\,[\,(T_s/100)^4 - (T_{sur}/100)^4\,]$$

What is the shape factor F?

This is a totally non-trivial question. It depends on the system geometry as well as the emissivities of the heater and of the surfaces surrounding it. For example:



Definitions:

$H = h/r_2$; $X = (1 - R^2)^{1/2}$
$R = r_1/r_2$; $Y = R(1 - R^2 - H^2)/(1 - R^2 + H^2)$

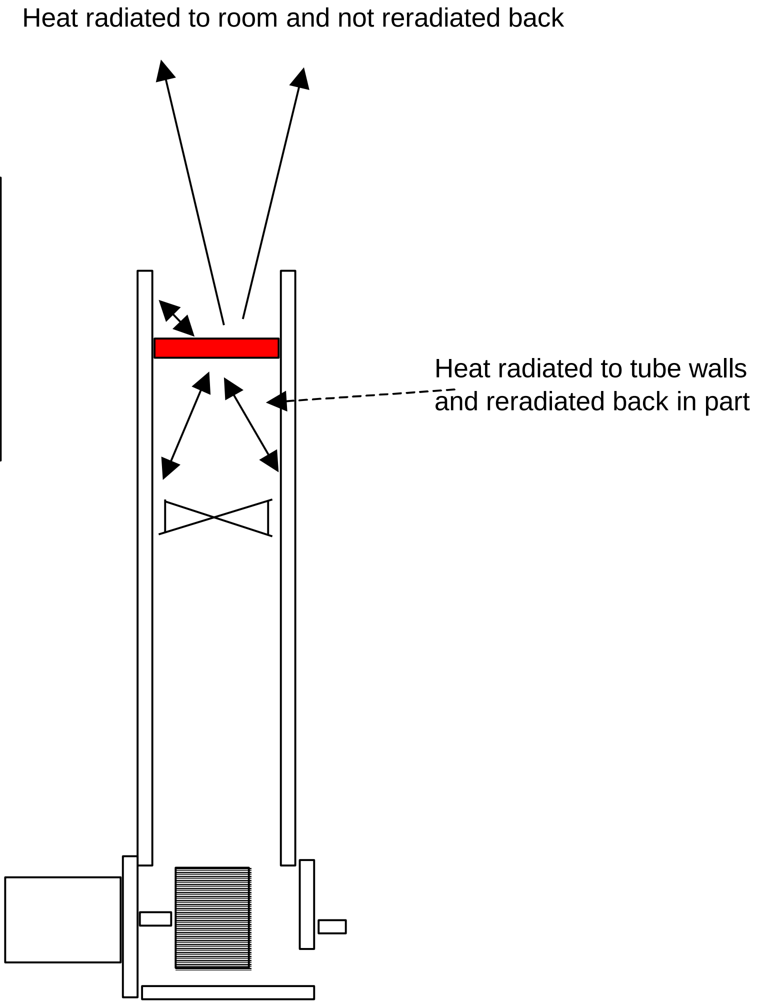
$$F_{1-2} = \frac{1}{\pi}\left\{R\left(\tan^{-1}\frac{X}{H} - \tan^{-1}\frac{2X}{H}\right) + \frac{H}{4}\left[\sin^{-1}\left(2R^2 - 1\right) - \sin^{-1}R\right] + \frac{X^2}{4H}\left(\frac{\pi}{2} + \sin^{-1}R\right) - \frac{\left[\left(1 + R^2 + H^2\right)^2 - 4R^2\right]^{1/2}}{4H}\left(\frac{\pi}{2} + \sin^{-1}Y\right) + \frac{\left(4 + H^2\right)^{1/2}}{4}\left[\frac{\pi}{2} + \sin^{-1}\left(1 - \frac{2R^2H^2}{4X^2 + H^2}\right)\right]\right\}$$

We won't go here in lab.

What is the shape factor F?

The shape factor F is related to the amount of radiant heat that is not reradiated vs versus the amount that is.

It is more complicated, but this is the basic idea.



Emissivity is a material property.

Emissivity has a value nominally from 0 to 1.

There is seemingly no logic to value vs materials.

It is VERY difficult to measure. We've tried.

Metal	Emissivity	Non-metal	Emissivity
Bare aluminum	0.02–0.4	Concrete (rough)	0.93–0.96
Gold	0.02–0.37	Glass	0.76–0.94
Copper	0.02–0.74	Wood	0.8–0.95
Lead	0.06–0.63	Carbon	0.96
Brass	0.03–0.61	Human skin	0.98
Nickel	0.05–0.46	Paper	0.7–0.95
Steel	0.07–0.85	Plastic	0.8–0.95
Tin	0.04–0.08	Rubber	0.86–0.94
Silver	0.01–0.07	Water	0.67–0.96
Zinc	0.02–0.28	Sand	0.76–0.9

DESIGN OBJECTIVE

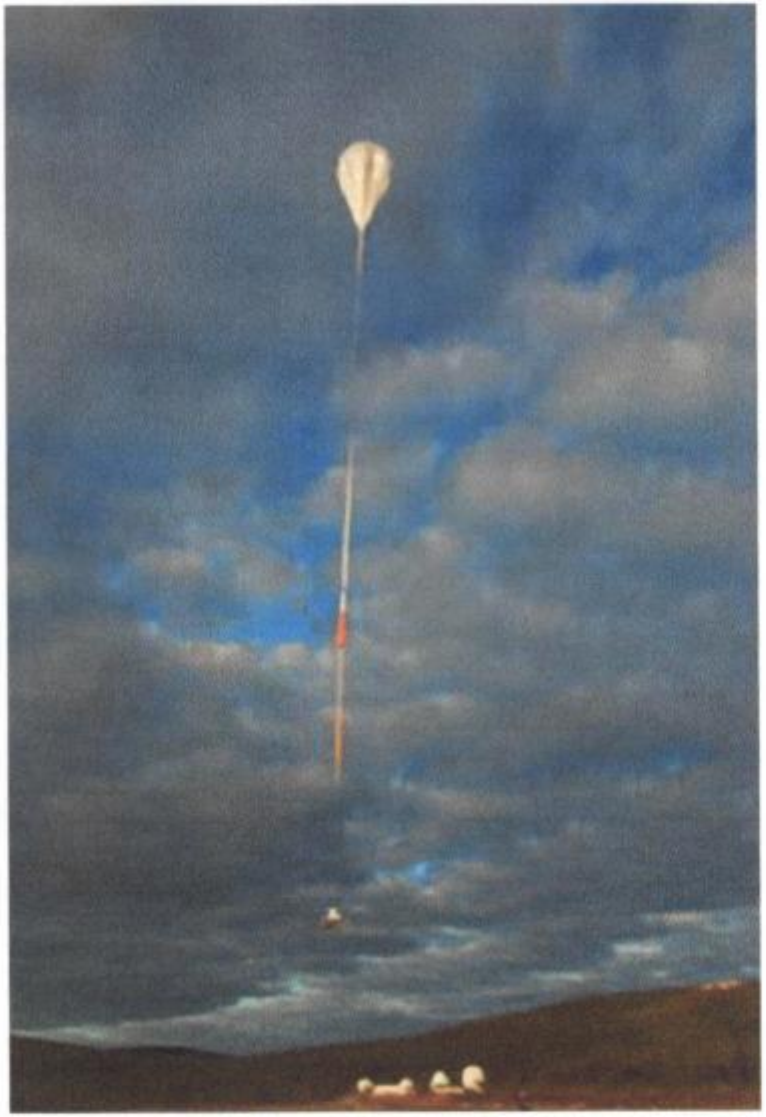
Heat transfer analysis of a high altitude physics instrument package.

UDel Dept of Physics has built and launched several of these over the years to study incoming cosmic particles

Another is being constructed for launch next year from McMurdo Station in Antartica.

The instrument package must be maintained at 20 C +/-
At both launch and altitude.

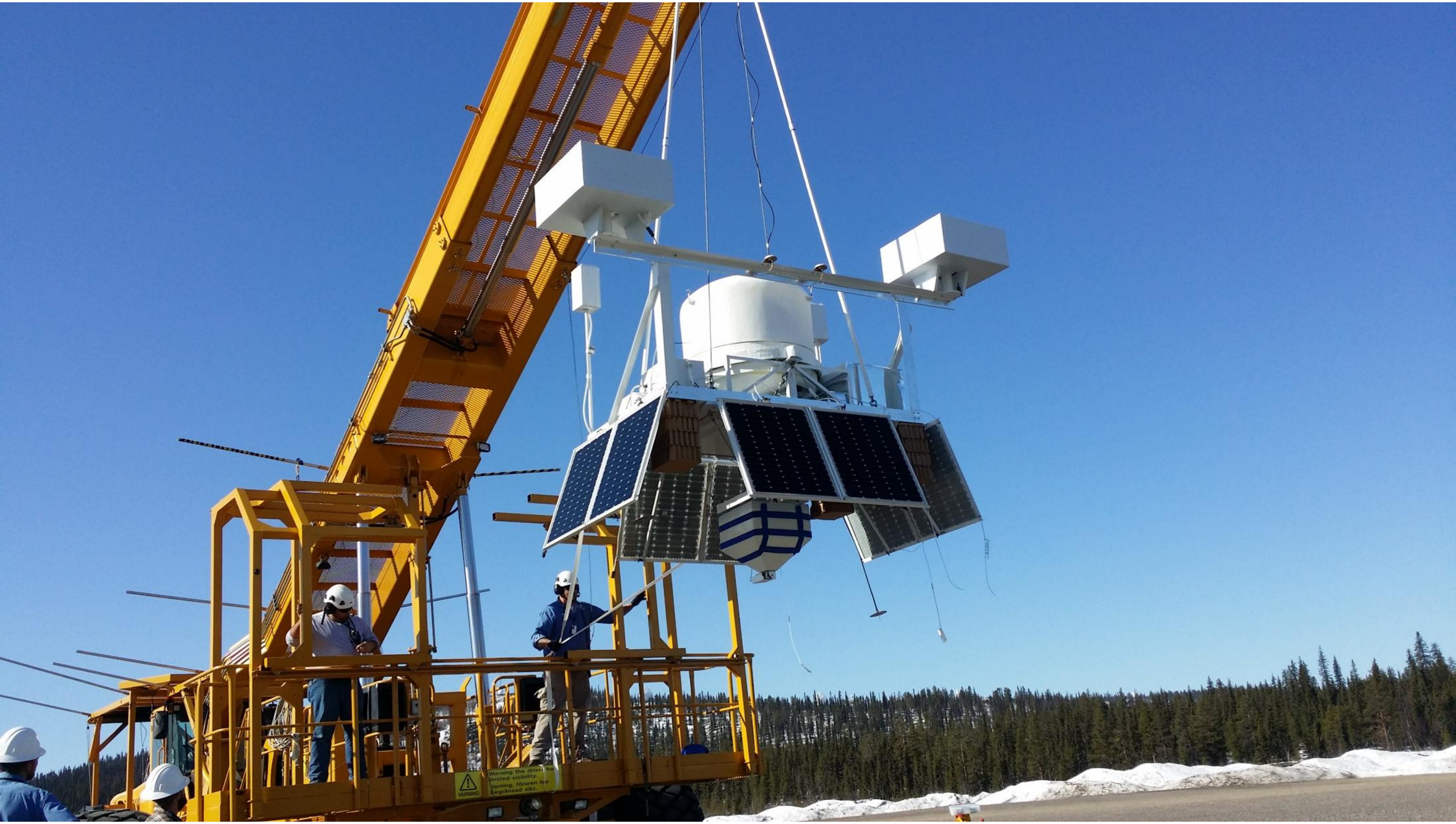
2006 AESOP Long
Duration Balloon Flight



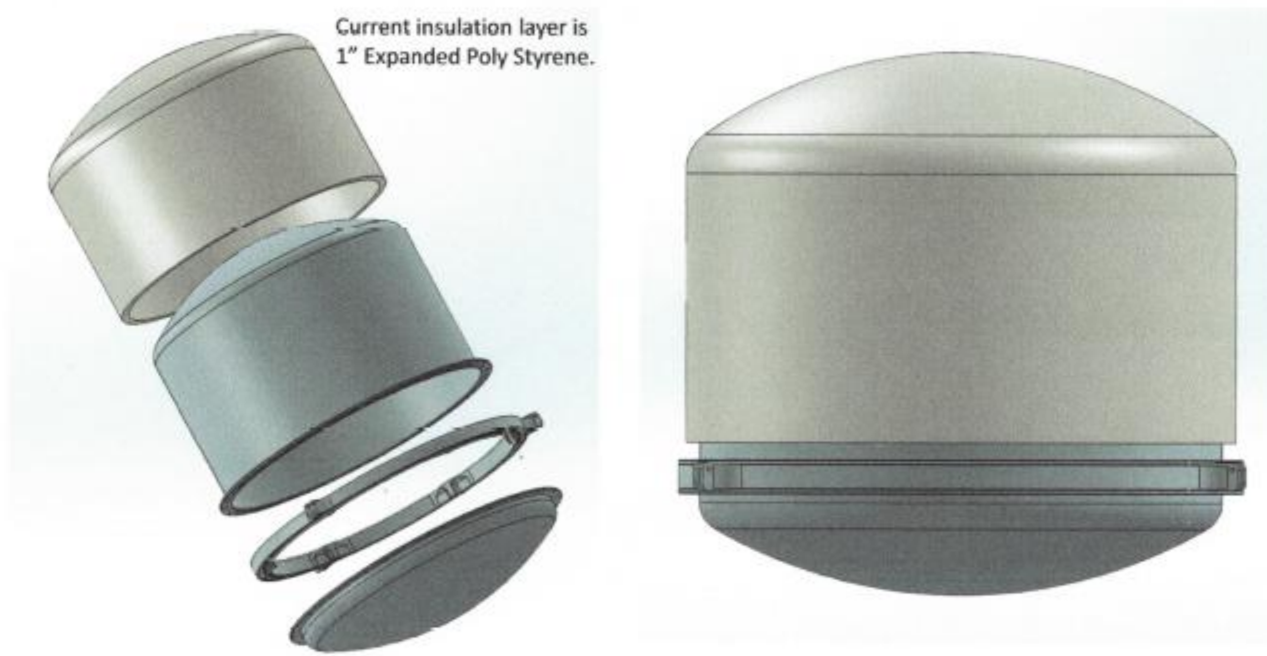
AESOP Depar

On ground before
launch: Cold air

At altitude, nil air,
but strong solar rad



AESOP-Lite Pressure Vessel



It is “Summer” in Antarctica now and will be at launch next year.

At McMurdo:

Max summer temp is 7 C
Winds average 12 knots

(At noon today: -17 C with wind 13 knots)

How do you keep instruments warm at launch?

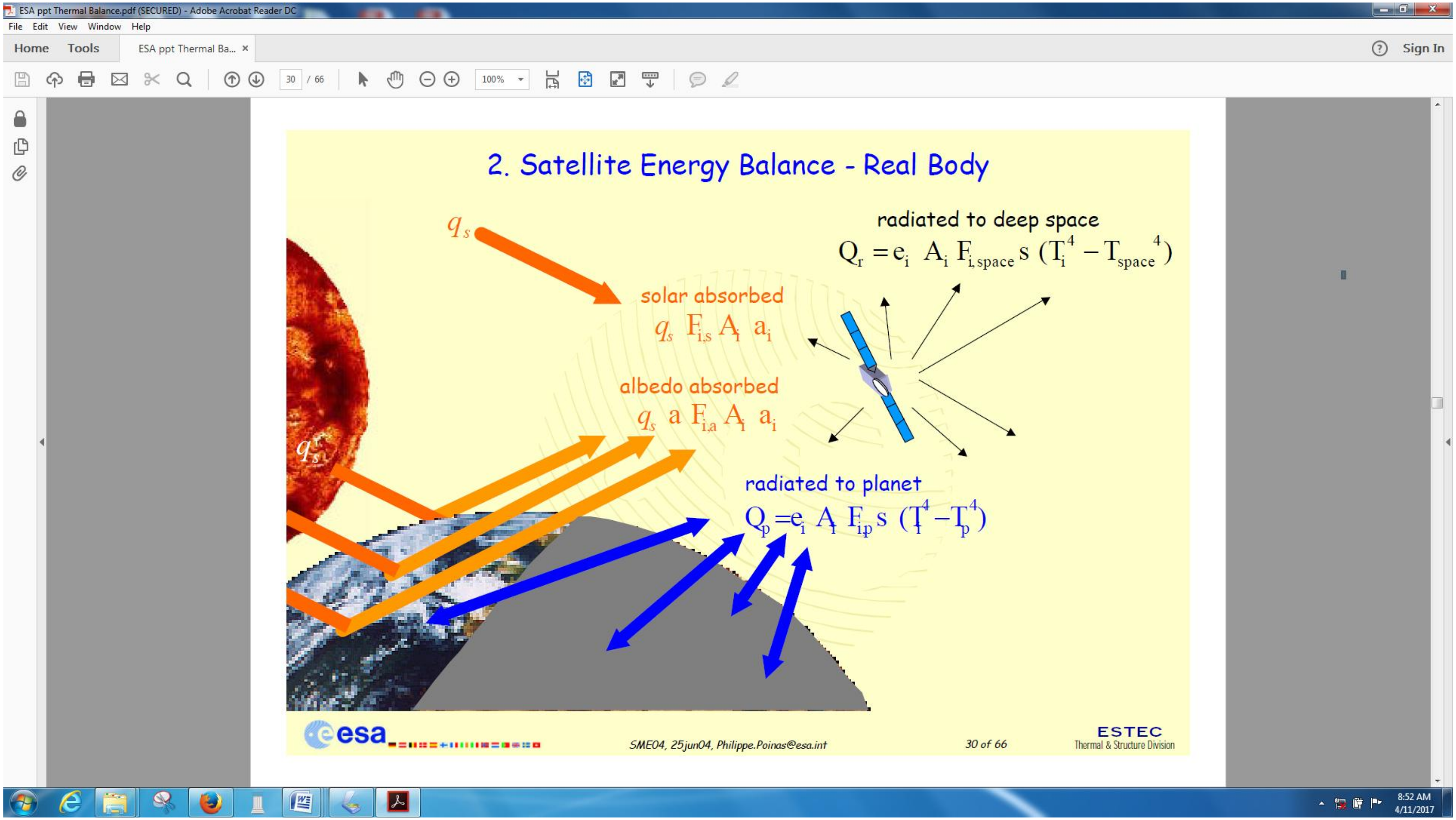
How do you keep the instruments cool at altitude?

We will do a much simplified, but realistic analysis.

Calculate the heater size (watts) to maintain inside temperature next flight in Antarctica:

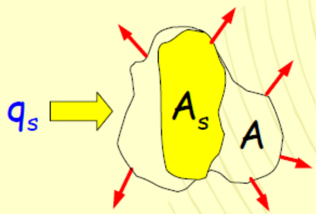
1. On the ground at launch at 7 C and 10 knot wind (forced convection, no solar irradiation)

2. At altitude, solar irradiation only. No convection.


2. Satellite Energy Balance - Real Body
radiated to deep space
$Q_r = e_i \; A_i \; F_{i,space} \; s \; (T_i^4 - T_{space}^4)$
q_s
solar absorbed
$q_s \; F_{i,s} \; A_i \; a_i$
albedo absorbed
$q_s \; a \; F_{i,a} \; A_i \; a_i$
radiated to planet
$Q_p = e_i \; A_i \; F_{i,p} \; s \; (T_i^4 - T_p^4)$
esa
SME04, 25jun04, Philippe.Poinas@esa.int
30 of 66
ESTEC
Thermal & Structure Division

2. Satellite Energy Balance - Real Body

- Real Body in Sun
  - assumes that body in infinitely conductive, no albedo, no planet flux
  - assumes that sink temperature is 0 K (not far from deep space)



T is independent of area A
depends only of α/ε

$$\boxed{\alpha\ A_s\ q_s = \varepsilon\ A\, \sigma\, T^4}$$

$$\boxed{T = \sqrt[4]{\frac{\alpha}{\varepsilon} F_s \frac{q_s}{\sigma}}}$$

$$\boxed{T = \sqrt[4]{\frac{\alpha}{\varepsilon}} \sqrt[4]{F_s}\ 394\ K}$$

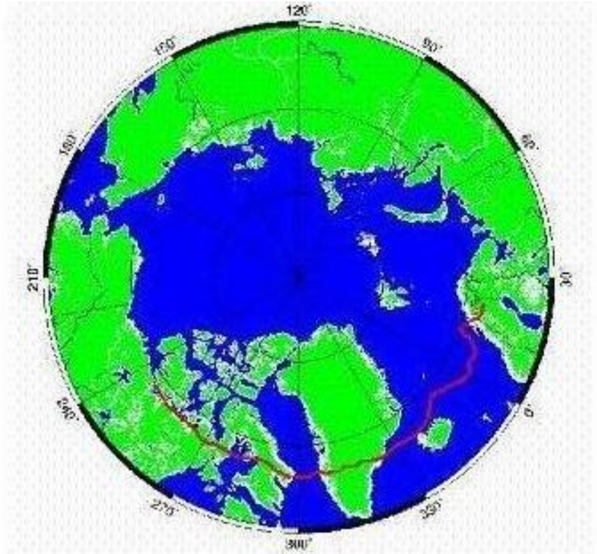
where F_S is the projected area $\boxed{F_s = \frac{A_s}{A}}$ with $q_s = 1367\ W/m^2$

esa

SME04, 25jun04, Philippe.Poinas@esa.int

31 of 66

ESTEC
Thermal & Structure Division


120°
150°
90°
180°
60°
210°
30°
240°
0°
270°
330°
300°