# PAYLOAD 1 CAPABILITIES - STANDARD OPERATIONS

**AOP Tech Note**

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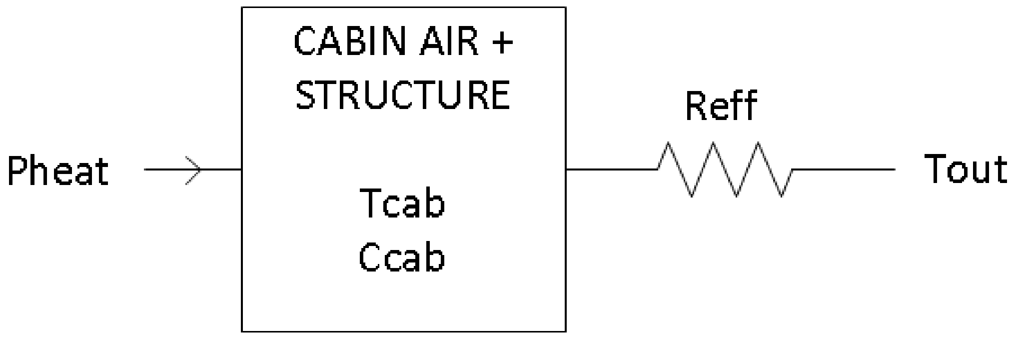
INTRODUCTION

This model estimates cabin and cooling loop temperatures for the hottest case within normal operations. This defining case was modeled, as opposed to one with more nominal temperatures, since the verification of this case ensures the success of the completely nominal temperature case. Since the chiller, aircraft, and all of the components are capable of producing heat, the coldest case is presently not of interest. The payload is capable of handling hotter tarmac temperatures, but this would be handled by a different model based on the Hot Weather Operations procedure.

DERIVATION OF EQUATIONS FOR THE AIRCRAFT CABIN

The diagram below shows the Cabin Air + Structure . This diagram indicates how heat is transferred. Tout represents the temperature outside the aircraft and is considered to be a heat sink with infinite heat capacity. Reff represents the effective thermal resistance between the Cabin Air + Structure and Tout. Reff is comprised of infiltration, due to the air drawin in by the chiller and the thermal resistance of the cabin, in parallel. Pheat is the combined heat power going into the cabin from sunlight, payload electronics, and airborne sensor operators.



$$\mathrm{Reff} = \frac{1}{\frac{1}{\mathrm{Rcab}} + \frac{1}{\mathrm{Rinfl}}}$$

$$\mathrm{Pcomb} = \mathrm{Psolar} + \mathrm{Pspect} + \mathrm{Paso}$$

In TN-20141216-EP-5.CabinThermalProperties, ignoring heat input from Rpim, we have shown that the cabin has the following (linear first order) differential equation

$$\frac{d}{dt}(\mathrm{Tcab} - \mathrm{Tout}) + \frac{\mathrm{Tcab} - \mathrm{Tout}}{\mathrm{Reff}\cdot\mathrm{Ccab}} = \frac{\mathrm{Pheat}}{\mathrm{Ccab}}$$

Since Tout is nearly always constant

$$\frac{d}{dt}\mathrm{Tcab} + \frac{\mathrm{Tcab}}{\mathrm{Reff}\cdot\mathrm{Ccab}} = \frac{\mathrm{Pheat}}{\mathrm{Ccab}} + \frac{\mathrm{Tout}}{\mathrm{Reff}\cdot\mathrm{Ccab}}$$

At t=inf,

$$\frac{\mathrm{Tcab\_inf}}{\mathrm{Reff}\cdot\mathrm{Ccab}} = \frac{\mathrm{Pheat}}{\mathrm{Ccab}} + \frac{\mathrm{Tout}}{\mathrm{Reff}\cdot\mathrm{Ccab}}$$

The solution is

$$\mathrm{Tcab}(t) = \mathrm{Tcab\_inf} - (\mathrm{Tcab\_inf} - \mathrm{Tcab\_0})\cdot e^{\left(\frac{-t}{\mathrm{Reff}\cdot\mathrm{Ccab}}\right)}$$

$$\mathrm{Tcab\_inf} = \mathrm{Pheat}\cdot\mathrm{Reff} + \mathrm{Tout}$$

At Tcab=infinity, the slope=0, so

$$\mathrm{Tcab\_inf} = \mathrm{Pheat}\cdot\mathrm{Reff} + \mathrm{Tout}$$

$$\mathrm{Texp}(\mathrm{Ta}, \mathrm{Tb}, \mathrm{RC}, t) := \mathrm{Tb} - (\mathrm{Tb} - \mathrm{Ta})\cdot e^{\frac{-t}{\mathrm{RC}}}$$

General transition temperature equation

**2015 PAYLOAD PARAMETERS**

HOT WEATHER PARAMETERS USED, BASED ON RELEASED 2015.04 TARMAC PROCEDURES

- Aircraft starts out in the hangar with doors open
- Doors and window vents are open during Tug and Tarmac GPU modes
- Window vents during Tarmac Survey and Airborne Survey modes

**CABIN THERMAL PROPERTIES**

$\mathrm{Rcab} := 0.011\,\frac{K}{W}$ Cabin thermal resistance, from TN-20141216-EP-6.CabinThermalProperties

$\mathrm{Ccab} := 8.403 \times 10^4\,\frac{J}{K}$ Cabin heat capacity, from TN-20141216-EP-6.CabinThermalProperties

$\mathrm{SHGC} := .81$ Solar heat gain coefficient of polycarbonate (http://www.danpalon.com/galleries/dynamic/userUploadFiles/File/Brochure_ENGLISH.pdf)

$\mathrm{Awind} := 16\cdot 50\mathrm{cm}\cdot 60\mathrm{cm} + 2\cdot 50\mathrm{cm}\cdot 40\mathrm{cm} + 2\cdot 60\mathrm{cm}\cdot 1\mathrm{m} = 6.4\,\mathrm{m}^2$ Twin Otter vistaliner window area (guesstimated)

$\mathrm{Psolar} := \left(1000\,\frac{W}{m^2}\right)\cdot\frac{\mathrm{Awind}}{2}\cdot\mathrm{SHGC}\cdot\cos\left(\frac{\pi}{4}\right) = 1.833 \times 10^3\,W$ Solar heat power input into airplane on tarmac, not including conduction. 1/2 of the windows are illuminated at 45deg incidence.

$\mathrm{Pspect} := 978W\cdot\frac{.62}{.89}$ Heat dissapated by the spectrometer, based on 2013 power budget X new DC efficiency

$\mathrm{Paso} := 232W\cdot 2$

$\mathrm{Pcomb} := \mathrm{Pspect} + \mathrm{Psolar} + \mathrm{Paso} = 2.978 \times 10^{3}\,\mathrm{W}$ Heat power input into airplane on tarmac, not including conduction (guesstimate)

$\mathrm{Ffan} := 525.3\,\frac{\mathrm{ft}^{3}}{\mathrm{min}}$ Chiller air flow rate (measured 2014.04.15)

Heat capacity of air $\mathrm{Cpair} := 1006\,\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}$

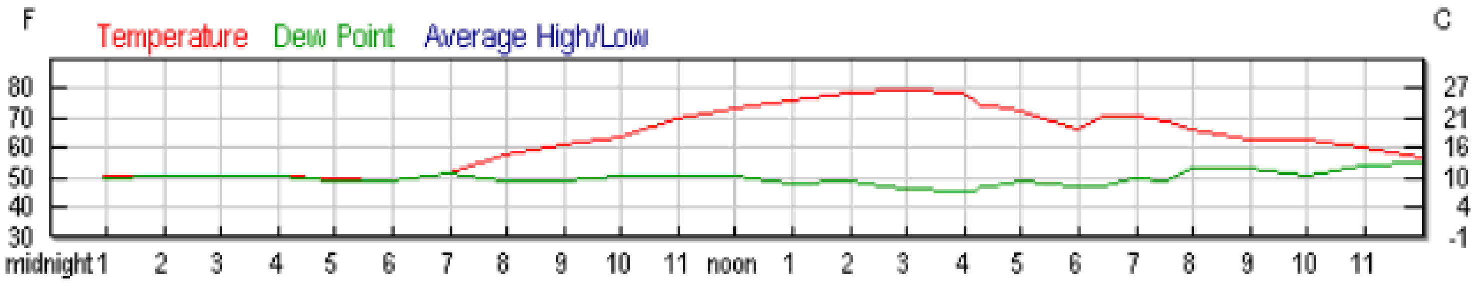
Density of Colorado air $\rho\mathrm{air} := 0.98\,\frac{\mathrm{kg}}{\mathrm{m}^{3}}$

$\mathrm{Rinfl} := \frac{1}{(\mathrm{Ffan}\cdot\mathrm{Cpair}\cdot\rho\mathrm{air})} = 4.091 \times 10^{-3}\cdot\frac{\mathrm{K}}{\mathrm{W}}$ Thermal resistance associated with infiltration, due to chiller fans pulling air in from outside

$\mathrm{Reff} := \frac{1}{\frac{1}{\mathrm{Rcab}} + \frac{1}{\mathrm{Rinfl}}} = 2.982 \times 10^{-3}\cdot\frac{\mathrm{K}}{\mathrm{W}}$ Effective thermal resistance of combined cabin with infiltration

## TEMPERATURE BOUNDARY CONDITIONS

This graph below is from the Denver International Airport on June 23rd, 2014. It shows how the temperature can rise throughout the day
it is not the absolute worst-case, but it can serve as a worst-case example. If we take off at 8AM, when it is 57°F and return at noon when it is 74°F. then our tarmac temperature should have risen by 9°C.



$\mathrm{Ttarm1} := 273.15\mathrm{K} + 26\mathrm{K}$ Morning temperature on the tarmac

$\mathrm{Thang1} := \mathrm{Ttarm1} - 12\mathrm{K}$ Morning temperature in the hangar, based on Fresno measurement $\mathrm{Tcabhang1} := \mathrm{Thang1} - 11\mathrm{K}$

$\mathrm{Tairb1} := \mathrm{Ttarm1} - 16\mathrm{K}$ Morning temperature at 1km AGL

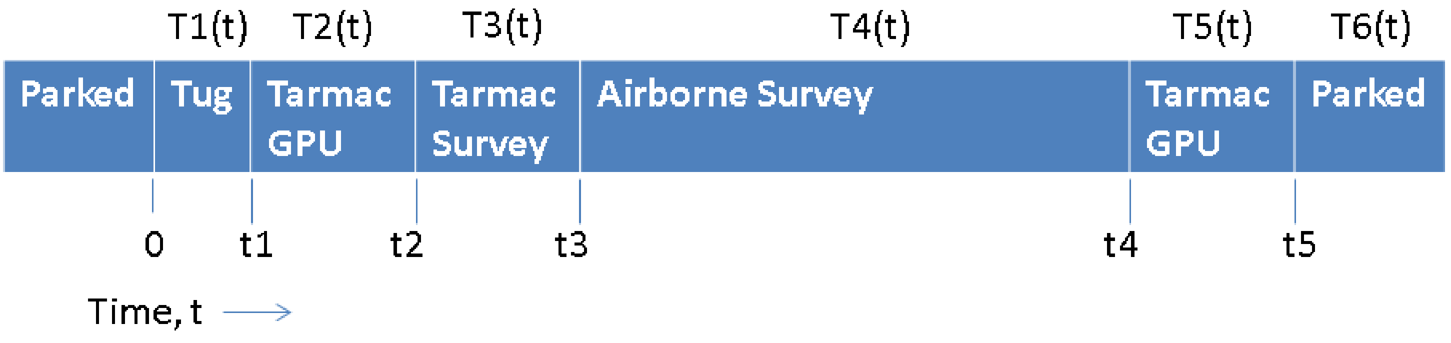
$\mathrm{Ttarm2} := \mathrm{Ttarm1} + 9\mathrm{K}$ Afternoon temperature on the tarmac

$\mathrm{Thang2} := \mathrm{Thang1} + 9\mathrm{K}$ Afternoon temperature of hangar

$\mathrm{Tairb2} := \mathrm{Tairb1} + 9\mathrm{K}$ Afternoon airborne temperature

$\mathrm{Tground2} := \mathrm{Tairb2} + 6\mathrm{K}$ Afternoon ground temperature

## TIMES AND TEMPERATURES



$\mathrm{t1} := 6\mathrm{min} \quad \mathrm{t2} := \mathrm{t1} + 5\mathrm{min} \quad \mathrm{t3} := \mathrm{t2} + 13\mathrm{min} \quad \mathrm{t4} := \mathrm{t3} + 4.2\mathrm{hr} \quad \mathrm{t5} := \mathrm{t4} + 6\mathrm{min}$

$\mathrm{T1}(t) := \mathrm{Texp}(\mathrm{Thang1} - 11\mathrm{K}, \mathrm{Ttarm1} + \mathrm{Pcomb}\cdot\mathrm{Reff}, \mathrm{Reff}\cdot\mathrm{Ccab}, t)$

$\mathrm{T2}(t) := \mathrm{Texp}(\mathrm{T1}(\mathrm{t1}), \mathrm{Ttarm1} + \mathrm{Pcomb}\cdot\mathrm{Reff}, \mathrm{Reff}\cdot\mathrm{Ccab}, t - \mathrm{t1})$

$\mathrm{T3}(t) := \mathrm{Texp}(\mathrm{T2}(\mathrm{t2}), \mathrm{Ttarm1} + \mathrm{Pcomb}\cdot\mathrm{Reff}, \mathrm{Reff}\cdot\mathrm{Ccab}, t - \mathrm{t2})$

$\mathrm{t4a} := 2\cdot\mathrm{Rcab}\cdot\mathrm{Ccab} \qquad \mathrm{t4b} := \mathrm{t4} - \mathrm{t3} - 2\cdot\mathrm{Rcab}\cdot\mathrm{Ccab}$

$\mathrm{T4a}(t) := \mathrm{T3}(\mathrm{t3}) + \frac{\mathrm{Tairb1} - \mathrm{T3}(\mathrm{t3} - \mathrm{t2})}{\mathrm{t4a}}\cdot t$

$\mathrm{T4b}(t) := \mathrm{T4a}(\mathrm{t4a}) + \frac{\mathrm{Tairb2} - \mathrm{T4a}(\mathrm{t4a})}{\mathrm{t4b} - \mathrm{t4a}}\cdot(t - \mathrm{t4a})$

$\mathrm{T4c}(t) := \mathrm{T4b}(\mathrm{t4b}) + \frac{\mathrm{Tground2} - \mathrm{T4b}(\mathrm{t4b})}{\mathrm{t4} - \mathrm{t3} - \mathrm{t4b}}\cdot(t - \mathrm{t4b})$

$$T4(t) := \text{if}\left[t - t3 < t4a, T4a(t - t3), \text{if}\left[t4a \le (t - t3) < t4b, T4b(t - t3), T4c(t - t3)\right]\right]$$

$$T5(t) := \text{Texp}(T4(t4), \text{Ttarm2} + \text{Pcomb}\cdot\text{Reff}, \text{Reff}\cdot\text{Ccab}, t - t4)$$

$$T6(t) := \text{Texp}(T5(t5), \text{Thang2} - 11\text{K}, \text{Reff}\cdot\text{Ccab}, t - t5)$$

Cabin temperature:

$$\text{Tcab}(t) := \text{if}(t < 0\text{min}, \text{Tcabhang1}, \text{if}(0 \le t < t1, T1(t), \text{if}(t1 \le t < t2, T2(t), \text{if}(t2 \le t < t3, T3(t), \text{if}(t3 \le t < t4, T4(t), \text{if}(t4 \le t < t5, T5(t), T6(t)))))))$$

**COOLANT LOOP MODEL**

Since 2/3 of the power from the thermal battery (TB) is due to heat capacity, it will be modeled as a thermal mass, until a more detailed model is created. This yields a more conservative result, since we are modeling with a decreased TB heat capacity, which has the effect of underestimating the coolant temperature buffering effect of the TB. Any increase in recovery time for the TB is not likely to be a problem because present measurements on TB refreezing time range from 0.5hr to 1.5hr, which is less than the 4.15hr flight time. TB refreezing time becomes inconsequential once we're able to shut down instruments upon survey end.

PARAMETERS

$\text{Ctb} := 1.417\cdot10^{4}\,\frac{\text{J}}{\text{K}}$ TB heat cap. from TN-20150401-EP-8

$\text{Ccool} := 4.474\cdot10^{4}\,\frac{\text{J}}{\text{K}}$ Cooling loop heat cap., from 2014.12.23 transient estimate

$\text{Rpim} := 0.075\,\frac{\text{K}}{\text{W}}$ PIM-air thermal resistance, from as-built measurements sheet

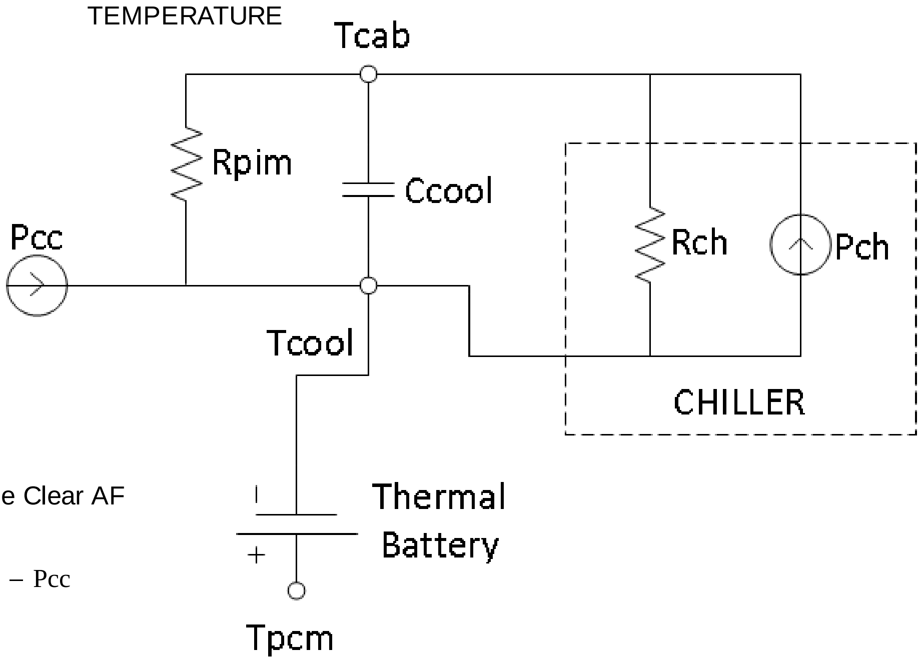
$\text{Rch} := \frac{1}{32.346\cdot.85}\,\frac{\text{K}}{\text{W}}$ Chiller thermal resistance, from SSCooling QA report

$\text{Pcc} := 512\text{W}$ Sunpower spec sheet

$\text{Pch} := 926.78\ \text{W}\cdot.85$ SSCooling QA report, derated for Ice Clear AF

$\text{Call} := \text{Ccool} + \text{Ctb}$ $\quad \text{Rall} := \frac{1}{\frac{1}{\text{Rpim}} + \frac{1}{\text{Rch}}}$ $\quad \text{Pall} := \text{Pch} - \text{Pcc}$

DIAGRAM SHOWING POWER TRANSFER AND TEMPERATURE



COOLING LOOP DIFFERENTIAL EQUATION

Power stored = Power in - Power out

$$\text{Call}\cdot\left(\frac{d}{dt}\text{Tcool}\right) = \frac{\text{Tcab} - \text{Tcool}}{\text{Rall}} - \text{Pall}$$

$$\left(\frac{d}{dt}\text{Tcool}\right) + \frac{\text{Tcool}}{\text{Rall}\cdot\text{Call}} = \frac{\text{Tcab}(t)}{\text{Rall}\cdot\text{Call}} - \frac{\text{Pall}}{\text{Call}}$$

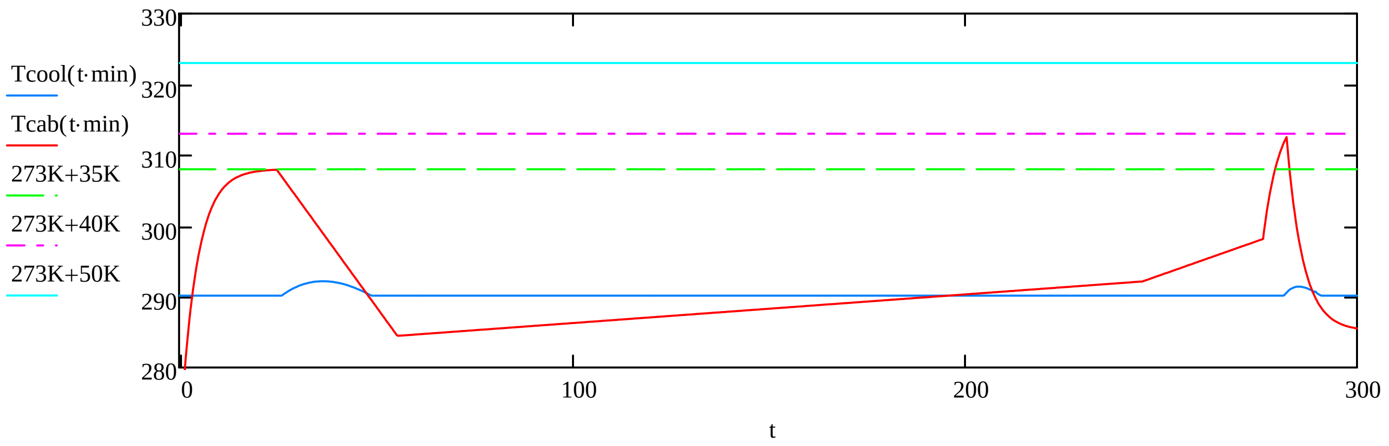
For equations of the form $\frac{d}{dt}\text{Tcool} + p(t)\cdot\text{Tcool} = q(t)$ $\quad p(t) := \frac{1}{\text{Rall}\cdot\text{Call}}$ $\quad q(t) := \frac{\text{Tcab}(t)}{\text{Rall}\cdot\text{Call}} - \frac{\text{Pall}}{\text{Call}}$

There is an integrating factor $\mu(tq) := e^{\int_0^{tq} p(t)\,dt}$ The solution is $\text{Tcool}(tq) = \frac{1}{\mu(tq)}\cdot\left(\int_0^{tq} \mu(t)\cdot q(t)\,dt + c1\right)$

Solve for c1 $\quad \text{Tcool}(0) = \frac{1}{\mu(0)}\cdot\left(\int_0^{0} \mu(t)\cdot q(t)\,dt + c1\right) = \text{Tcool0}$ $\quad c1 = \text{Tcool0}$ $\quad \text{Tcool0} := \text{Thang1} - 11\text{K}$

$$\text{Tset} := 273.15\text{K} + 17\text{K}$$

$$\text{Traw}(tq) := \frac{1}{\mu(tq)}\cdot\left[\left(\int_0^{tq} \mu(t)\cdot q(t)\,dt\right) + \text{Tcool0}\right] \qquad \text{Tcool}(tq) := \text{if}(\text{Traw}(tq) < \text{Tset}, \text{Tset}, \text{Traw}(tq))$$



CABIN AND COOLANT TEMPERATURE AS A FUNCTION OF TIME

NOTE: valid for morning tarmac air temperature $\mathrm{Ttarm1} - 273.15\mathrm{K} = 26\,\mathrm{K}$

RESULTS

In the above graph, you can see that the cabin temperature is within the released requirement of 40°C (NEON.AOP.4.1041). This means that Flight Ops to only survey when the morning tarmac air temperature is <=26°C. For hotter tarmac temperatures, the Hot Weather Operations procedure is used.

For each cabin heating, the delayed rise in coolant temperature is due to the heat capacity of the thermal battery and cooling loop absorbing heat before the chiller power capacity is exceeded.

CONCLUSIONS

1. As long as the morning tarmac air temperature is <=26°C, all of the NEON temperature requirements are met for the cabin and cooling loop temperatures
2. Since requirement NEON.AOP.4.1041 is hotter than the LiDAR rack requirement of 35°C, there is some risk of overheating. This may not be an issue, since it is a brief temperature excursion. An Optech temperature sensor within the LiDAR rack will alert us of an overtemperature condition.
3. For future operating procedure planning, the first goal should be to shut down the LiDAR and spectrometer after the survey.