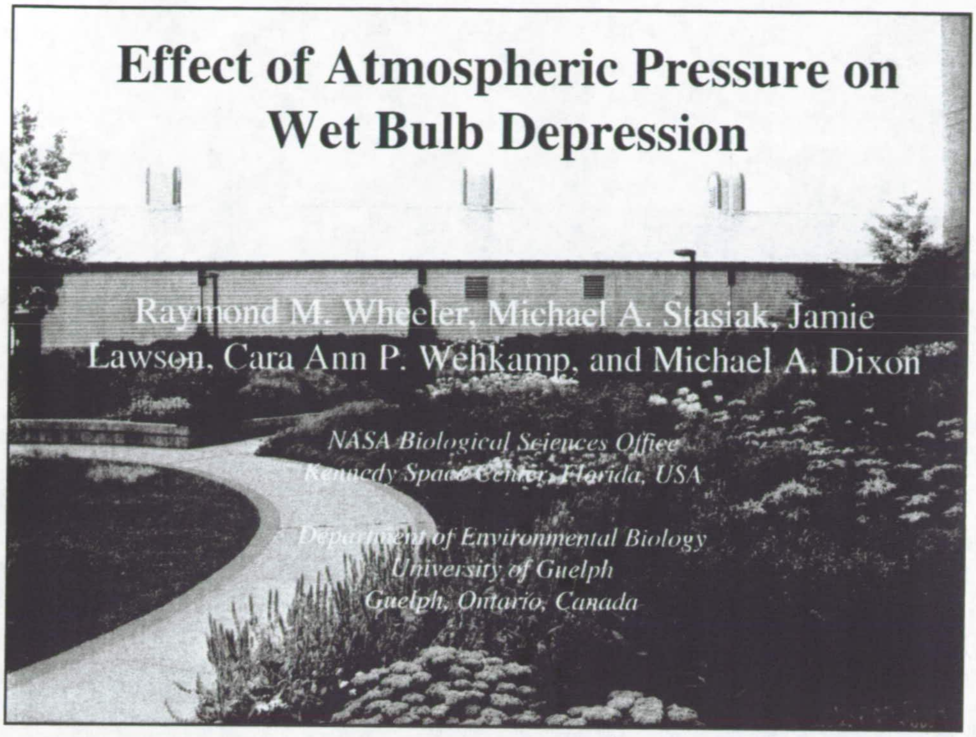

Reduced Pressures for Space Missions?

- Reduced gas leakage and hence reduced resupply costs
- Reduced structural mass
- Increased potential for finding transparent materials for space "greenhouses"
- Rapid egress for EVAs (spacewalks) without prolonged prebreathing and acclimation

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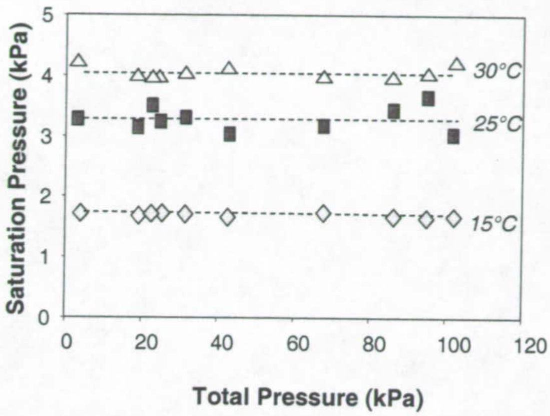
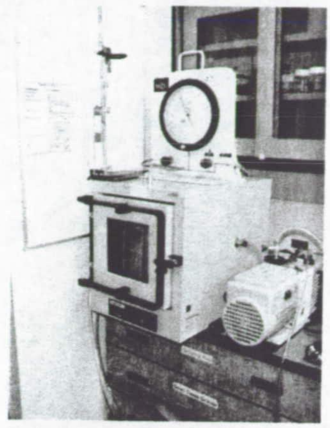
- How do environmental sensors perform at reduced pressures?

Effect of Pressure on Saturation Vapour Pressure

(Rygalov et al., 2004, *NASA Ken Space Center, FL*)





Steam table values for e_s: 30ºC = 4.24 kPa; 25ºC = 3.17 kPa; 15ºC = 1.70 kPa (Kennan, Keyes, et al., 1978)

Different Equations for Calculating Saturation Water Vapour Pressures

Goff-Gratch (1946) / and Smithsonian Tables (1984)

$$\begin{aligned}\mathrm{Log}_{10}\, p_w = & -7.90298\,(373.16/T-1) \\ & + 5.02808\,\mathrm{Log}_{10}(373.16/T) \\ & - 1.3816\; 10^{-7}\,(10^{11.344\,(1-T/373.16)} - 1) \\ & + 8.1328\; 10^{-3}\,(10^{-3.49149\,(373.16/T-1)} - 1) \\ & + \mathrm{Log}_{10}(1013.246)\end{aligned}$$

with T in [K] and p_w in [hPa]

Hyland and Wexler (1983)

$$\begin{aligned}\mathrm{Log}\, p_w = & -0.58002206\; 10^{4} / T \\ & + 0.13914993\; 10^{1} \\ & - 0.48640239\; 10^{-1}\, T \\ & + 0.41764768\; 10^{-4}\, T^2 \\ & - 0.14452093\; 10^{-7}\, T^3 \\ & + 0.65459673\; 10^{1}\, \mathrm{Log}(T)\end{aligned}$$

with T in [K] and p_w in [Pa]

Magnus Teten (Murray, 1967)

$$\mathrm{Log10}\; p_w = 7.5\, t / (t+237.3) + 0.7858$$

with t in [°C] and p_w in [hPa]

Buck (1981, 1996)

$p_w = 6.1121\; e(18.678 - t / 234.5)\; t / (257.14 + t)$ [1996]

$p_w = 6.1121\; e17.502\; t / (240.97 + t)$ [1981]

with t in [°C] and p_w in [hPa]

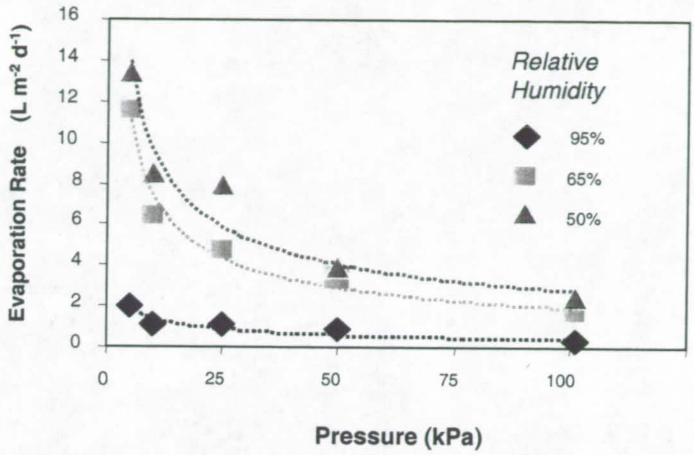
Sonntag (1994)

$$\begin{aligned}\mathrm{Log}\, p_w = & -6096.9385 / T \\ & + 16.635794 \\ & - 2.711193\; 10\text{-}2 * T \\ & + 1.673952\; 10\text{-}5 * T^2 \\ & + 2.433502 * \mathrm{Log}(T)\end{aligned}$$

with T in [K] and p_w in [hPa]

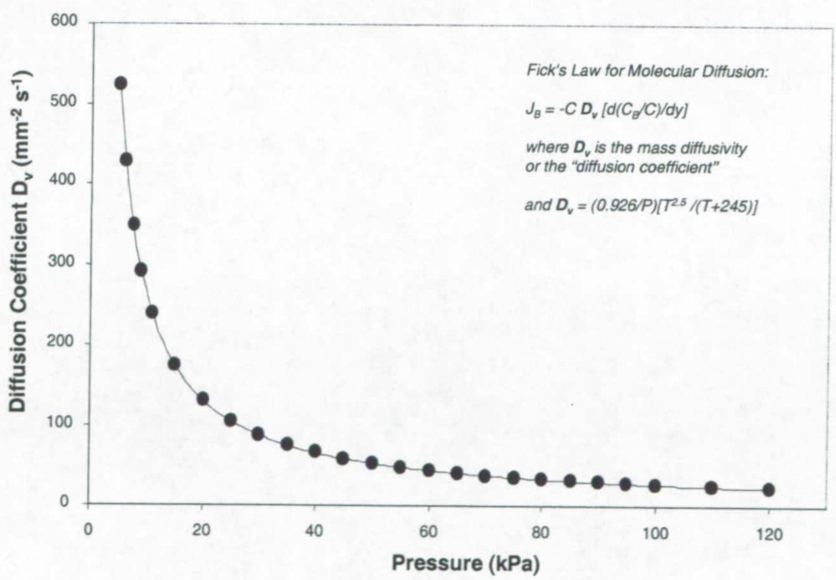
Effects of Pressure on Evaporation Rates

(Rygalov et al., 2004)



→ *Related to increased gas diffusion rates at reduced pressures*

Diffusion Coefficient (D_v) of Water Vapour at 25ºC



If evaporation rates increase at reduced pressures.....

then wet-bulb (WB) depression should also increase.

Psychrometric Equation

using Wet Bulb Temperature

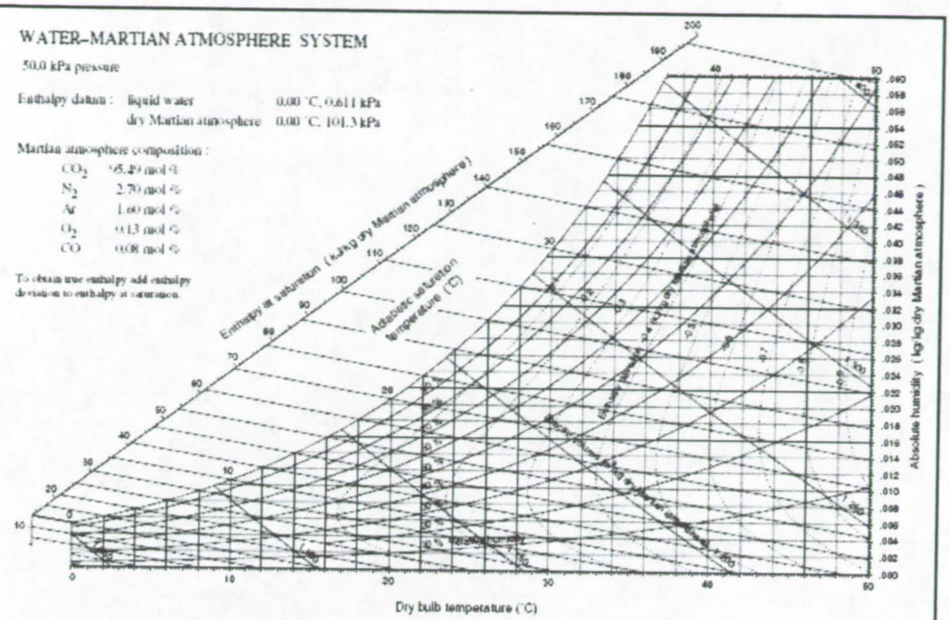
$$e_s' = e + \gamma (T_{db} - T_{wb})$$

γ = the psychrometric constant

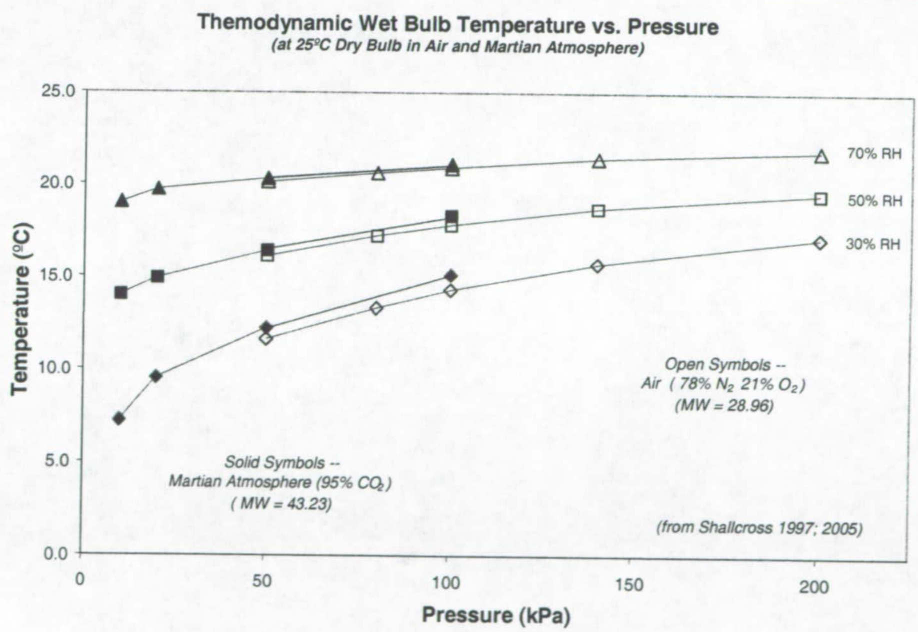
where $\gamma = p A$

with p = pressure and $A \approx 6.53 \times 10^{-4}\ K^{-1}$ for average size thermometers and aspiration rate of 4 m s^{-1}

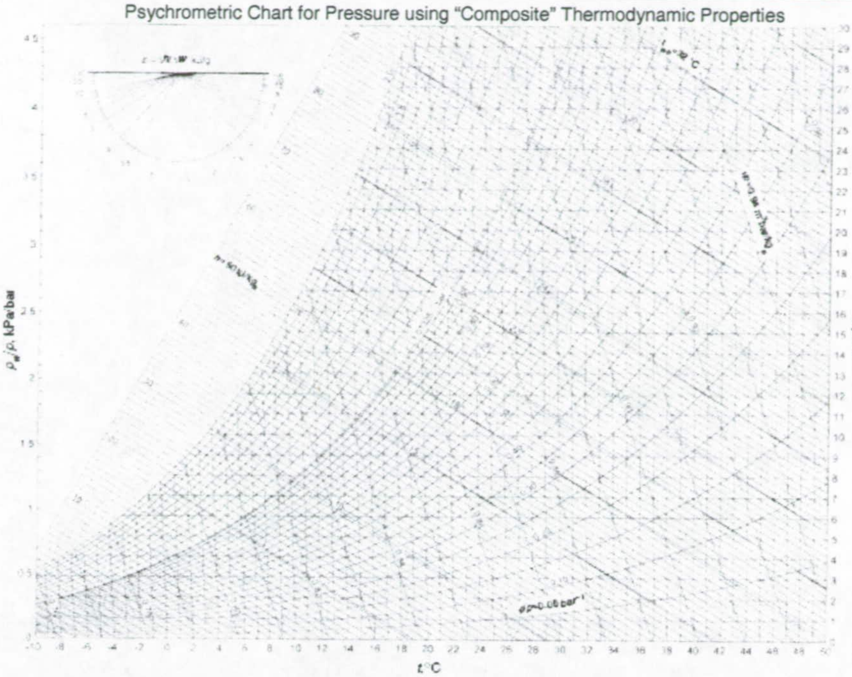
But e_s' is saturation vapour pressure at the wet bulb temperature ! Thus this equation can't be used the to solve directly for T_{wb}.



Psychometric chart for water vapor in Martian atmosphere brought to 50 kPa pressure.
From: D.C. Shallcross. 2005. Intl. J. Heat and Mass Transfer 48:1785-1796.

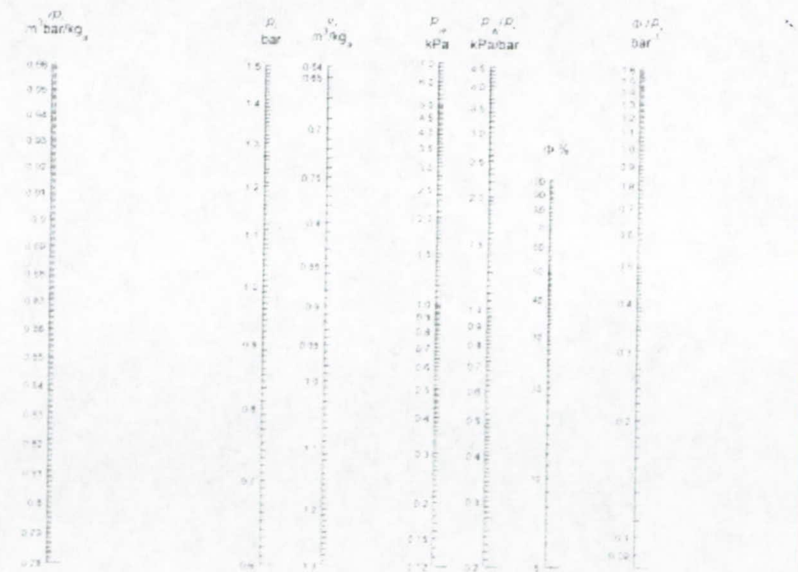


Psychrometric Chart for Pressure using "Composite" Thermodynamic Properties

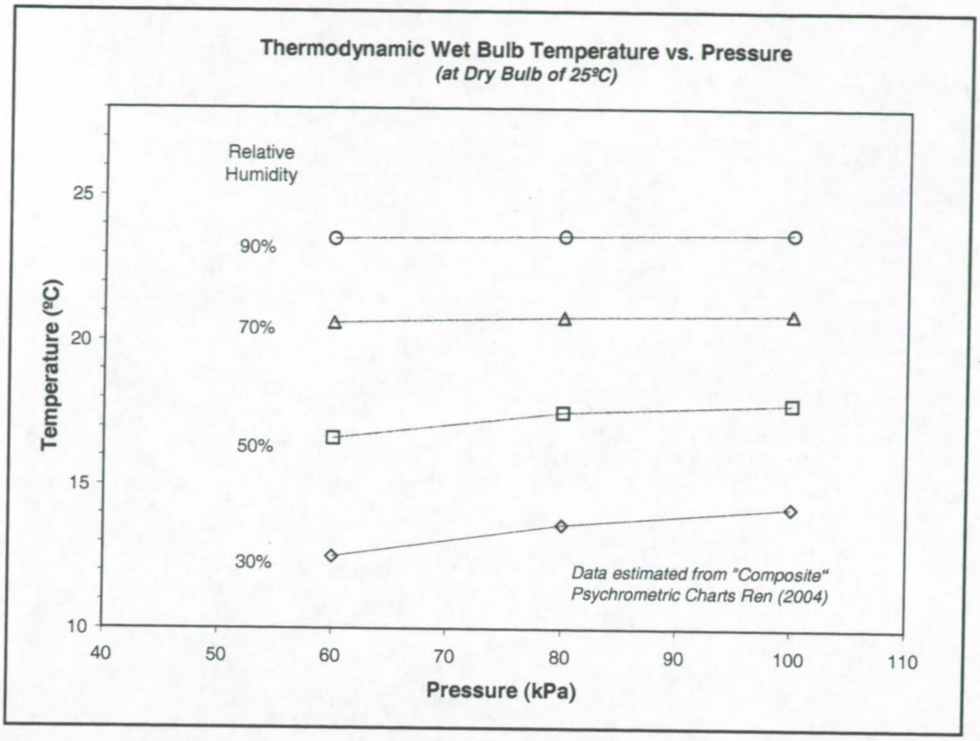


H.-S. Ren. 2004. Construction of a generalized psychrometric chart for different pressures. J. Mech. Eng. Ed. 32(3):212-222.

Composite Psychrometric Chart Nomograph



H.-S. Ren. 2004. Construction of a generalized psychrometric chart for different pressures. J. Mech. Eng. Ed. 32(3):212-222.



Our objective was to directly measure wet bulb depression at different pressures and compare our results published psychrometric models for pressure effects.

Experimental Approach

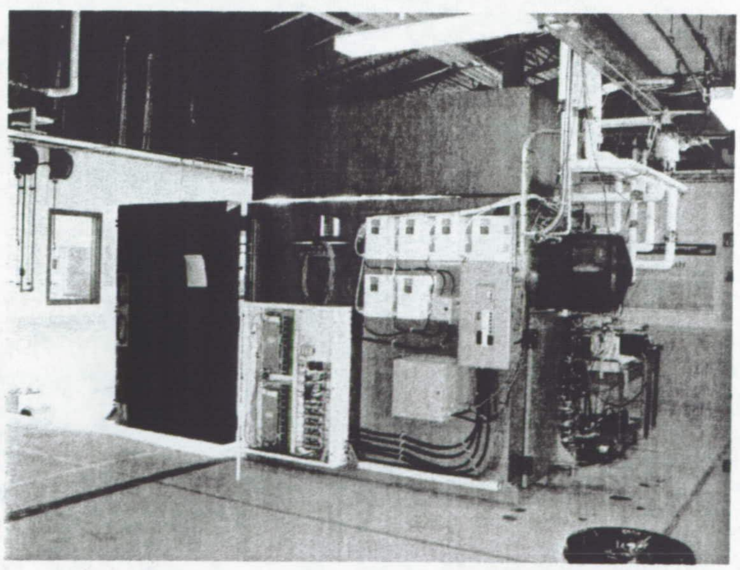
•Measure wet bulb temperatures five different pressures and three different relative humidities:

–Pressures: 10, 20, 50, 80, and 100 kPa

–Relative Humidities: 30, 50, and 70%

Each combination allowed to equilibrate for at least 90 minutes, then a 30-min segment of data was averaged for WB, DB, Dew Point, Chamber Air Temperature, Chamber RH, and Water Temperature

Hypobaric Test Chamber
University of Guelph, CESF

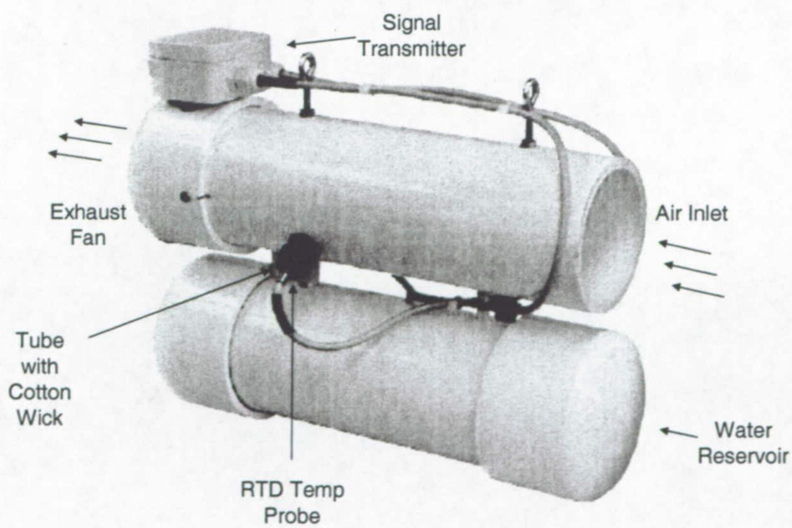


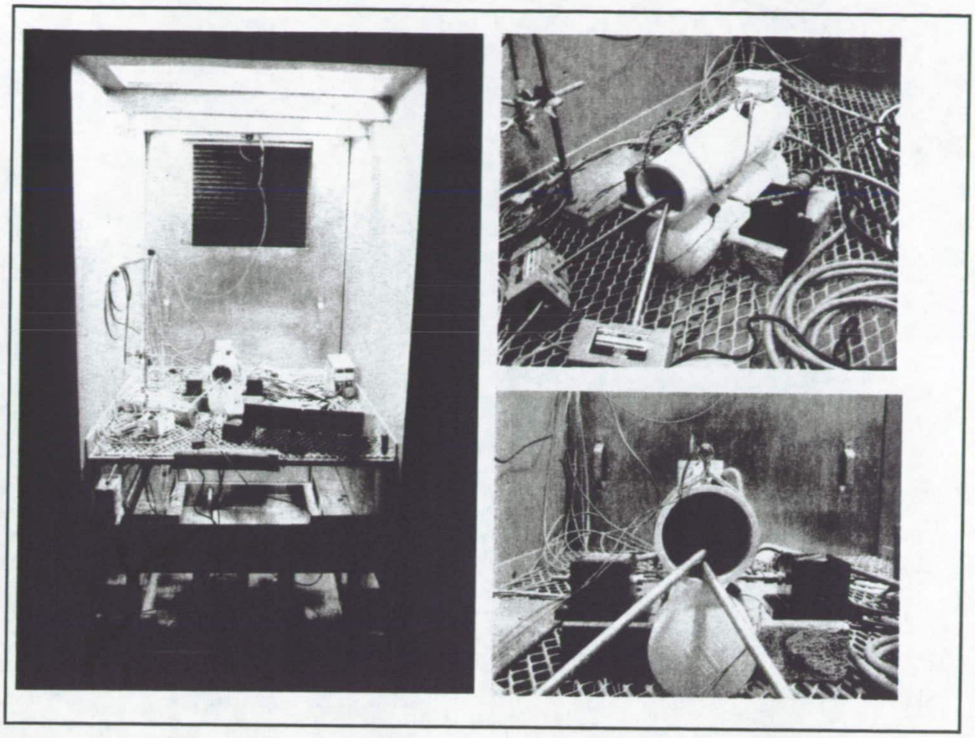
Environmental Monitoring and Control:

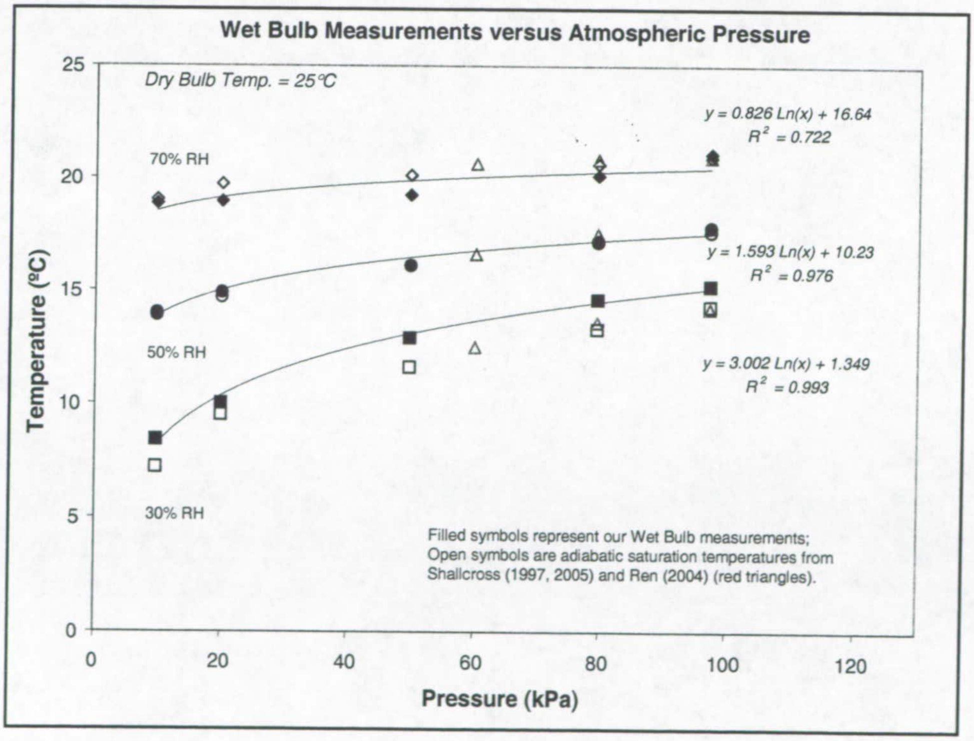
- Wet Bulb / Dry Bulb
  - Enercorp Model HT-WD-A Psychrometer
    - Two matched platinum RTD temperature probes
    - Constant aspiration -- 3 m s^{-1}
- Humidity Control
  - Honeywell Model HIH-3602-A Capacitance Sensors (2)
- Temperature Control
  - Argus TN 21 Thermisters (2)
- Dew Point Measurements
  - General Eastern Model 1100DP (1)
- Humidity Calibration / Comparison *(at 100 kPa)*
  - Vaisala HMP42 Handheld RH/Temp Probe
- Pressure Monitoring / Control
  - MKS 'Barotron' Capacitance Manometer
- Water temperature for the psychrometer reservoir

Wet / Dry Psychrometer

Enercorp Inst. Ltd. (Model HT-WD-A)



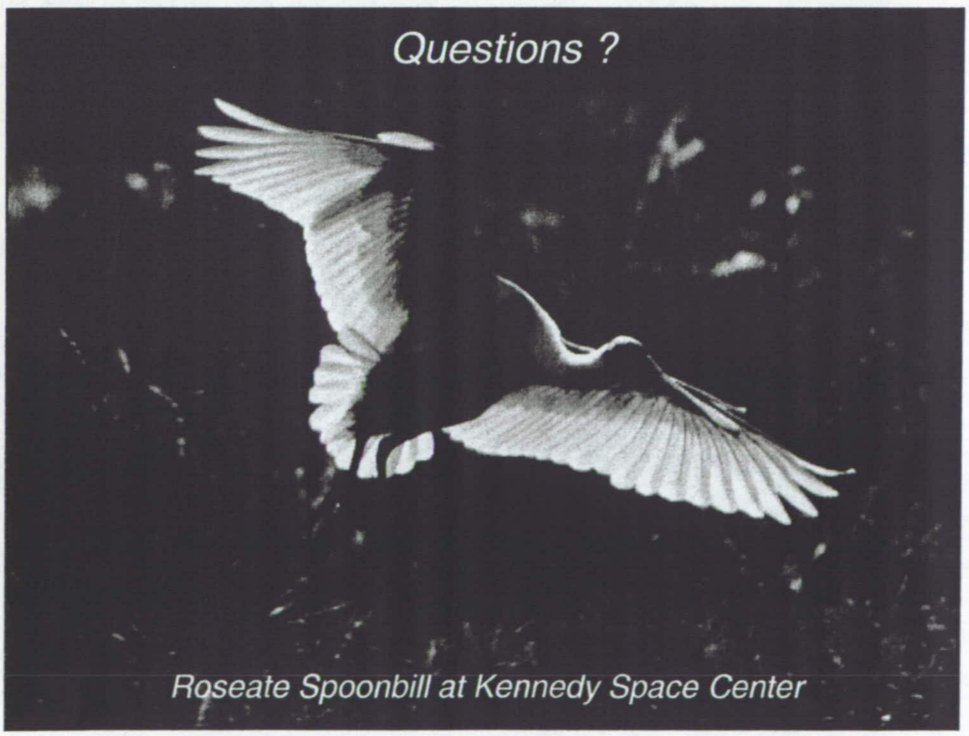




Wet Bulb Measurements versus Atmospheric Pressure
Dry Bulb Temp. = 25°C
y = 0.826 Ln(x) + 16.64
R² = 0.722
70% RH
y = 1.593 Ln(x) + 10.23
R² = 0.976
50% RH
y = 3.002 Ln(x) + 1.349
R² = 0.993
30% RH
Filled symbols represent our Wet Bulb measurements; Open symbols are adiabatic saturation temperatures from Shallcross (1997, 2005) and Ren (2004) (red triangles).
Temperature (ºC)
Pressure (kPa)
0
5
10
15
20
25
0
20
40
60
80
100
120

Conclusions

- Our measurements of wet bulb depression at different pressures matched the modeled adiabatic saturation temps reasonably well.
- At a dry bulb temp of 25°C, the normal wet bulb temp for 30% RH and 100 kPa is ~15°C, but this dropped to ~8°C at 10 kPa.
- The results suggest that psychrometers need direct calibration at the target pressures or that pressure corrected charts are required.
- For a given vapour pressure deficit, any moist surfaces, including transpiring plant leaves, will be cooler at lower pressures due to the increased evaporation rates.



Roseate Spoonbill at Kennedy Space Center

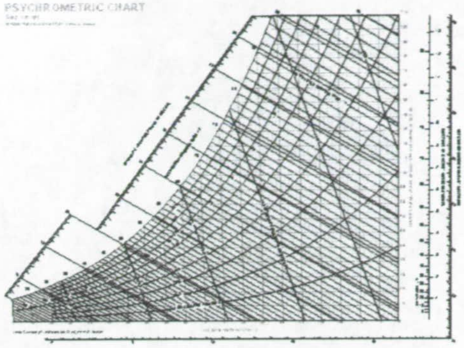
Back up Slides

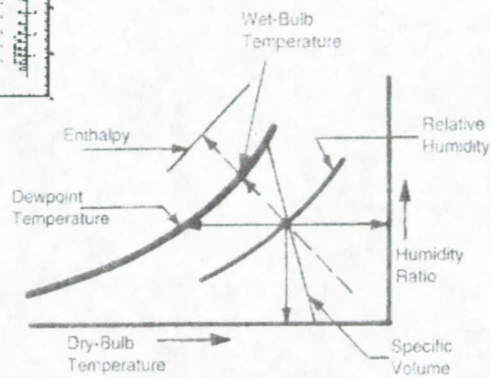
Wet Bulb Temperature vs. Adiabatic Saturation Temperature

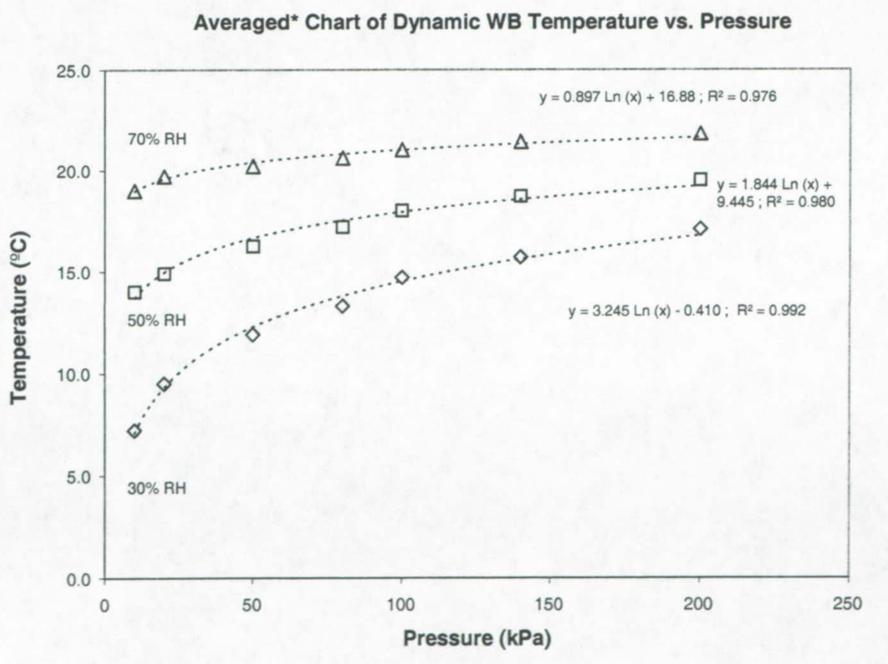
Wet Bulb Temperature: The temperature of a sensor covered with pure water that is evaporating freely into the ambient air stream. Typically taken with a "matched" dry bulb (DB) reading under constant aspiration (3-5 m s^{-1}) and shielded from radiation. But WB readings can be affected by the aspiration rate, mass of the sensor, water temperature, properties of the wick, and water purity.

Adiabatic Saturation Temperature (also called Thermodynamic Wet Bulb Temperature): The thermodynamic state resulting from adiabatic saturation, where there is no heat or mass transfer involved, and is independent of the measurement technique.

The Psychrometric Chart







Data for 12 and 20 kPa for CO_2 (95%) atmosphere; 80, 140, and 200 kPa for air; 50 and 100 averaged for CO_2 and air (Shallcross, 1997).