Week 2, Wed
180-265?

Pete:
1) Discuss Video / Reading
2) Questions on reading / videos

DH:
3) Power Generation

Reading from DH
"CCGT [I call them NGCC] is the best ***supply side*** advance since the oil embargo"
"If the US switched ½ of its grid coal to CCGT, we'd save 8.5 quads/yr."
"…$0.40 / Watt to construct"…. *Capital costs*
"$0.03/kWh at the buss bar" …. *Operational costs*

LNG explosion Skikda, Algeria was an accident, killed 27

ASHRAE – American Society of Heating, Refrigeration and Air conditioning Engineers

Brownfield is a term used in urban planning to describe land previously used for commercial uses or industrial purposes. Such land has been contaminated with hazardous waste or pollution or is feared to be so.[1][2] Once cleaned up, such an area can become host to a business development such as a retail park.

CAL POLY
SAN LUIS OBISPO

News
University News & Information

FOR IMMEDIATE RELEASE
Jan. 23, 2015

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Cal Poly's Warren J. Baker Center Receives LEED Gold Certification

SAN LUIS OBISPO — Cal Poly's Warren J. Baker Center for Science and Mathematics has been awarded gold for being green. The 189,000-square-foot structure, which opened for classes in September 2013, earned LEED gold certification by the U.S. Green Building Council earlier in January.

LEED — Leadership in Energy and Environmental Design — is the national benchmark for the design, construction and operation of high-performance green buildings. Certification means a building has met rigorous standards for sustainability, water and energy efficiency, resource selection and environmental quality.

Physics of Buildings

David Hafemeister

Cal Poly University

Adapted from Chapters 11 and 12:

Physics of Societal Issues:

Calculations on National Security, Environment and Energy

(Springer, 2007)

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Energy in Buildings

- **Linearized Heat Transfer**
- **Free Temperature**
- **Scaling Model of a Cubic Building**
- **Passive Solar Heating**
- **Thermal Flywheel House**

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Linearized Heat Transfer

DC Circuits: $V = I R$, similar to

Heat Conduction: $dQ/dt = UA\Delta T = (1/R)A\Delta T$

U => Btu/ft^2-hr-°F = 1 Art (Henry Kelly)
(W/m^2-°C)

Steady state heat transfer is similar to DC circuits

V =	I	R
ΔT =	dQ/dt	(R/A)

This ignores heating up/down, important in CA, less so Chicago

mass similar to capacitance, $V = Q/C$ and $\Delta T = \Delta Q\ (1/mc)$

mass and R are continuous media, a leaky capacitor

no heat inductance, $V = L\ (dI/dt)$, needs d^2Q/dt^2

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Radiation: $dQ/dt_{radiation} = \sigma A(\varepsilon_i T_i^4 - \varepsilon_o T_o^4) = U_{radiation} A\Delta T$

$U_{radiation} = 4\varepsilon\sigma T_1^3 = (4\varepsilon)(5.7 \times 10^{-8})(293\ K)^3 = 5.7\ \varepsilon\ SI = 1\ \varepsilon\ UK$

Convection = f(geometry, wind, surface)

$dQ/dt_{convection} = hA(\Delta T)^{5/4} = (h\Delta T^{1/4})A\Delta T = U_{convection} A\Delta T$

$U_{convection} \approx U_{radaiation}$

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Free Temperature

Old House, 40x40= 1600 ft^2 x 10 ft ceiling, sum of UA's

walls(R5),	1600-400 ft^2 x U0.2	= 240
ceil/floor(R10),	1600 ft^2 x U0.1 x 1.5	= 240
window(R1),	400 ft^2 x U1	= 400

Lossiness = ΣUA =
240 + 240 + 400 + 30% infil. =1150 Btu/hr-°F

Free temperature rises with 1 kW (3500 Btu/hr) of internal heat i

ΔT_{free} =(dQ/dt)/ΣUA = 3500/1150 = 3°F

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$T_{balance} = T_{thermostat} - \Delta T_{free}$ = 68 °F - 3 °F = 65 °F

with 2 kW (x 2) and 200 Btu/hr-°F (x 1/5): ΔT_{free} = 35°F

No heating needed until 35°F

10% heating needed at 0°F

[20% loss rate][70 – 35 – 0°F]/[70 – 0 °F] = 0.2 x 0.5 = 0.1

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Annual Energy Use

Large buildings are driven more by internal heat loads.

Small buildings are driven by climate and their skins.

Degree days are less relevant to CA, as compared to Chicago

Degree Days: Annual Heat Loss Q = $\Sigma\Sigma$ (dQ/dt) Δt

$Q = \Sigma^n U_j A_j\ \Sigma^{8766} (T_{base} - T_{outside})_i$(1 hour)

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degree-hours per year (*dh/yr*):

$dh/yr = \Sigma^{8766} (T_{base} - T_{outside})_i$(1 hour)

degree-days per year (*dd/yr*):

$dd/yr = \Sigma^{8766} (65°F - T_{outside})_i$(1 hour)/24

Q_{needed} = (*dd/yr*)(24 hr/day)(1/efficiency) $\Sigma^n U_j A_j$

Chicago (6200 dd), lossiness improved to 600

Q = (6200 dd/y)(24)(3/2)(600) = 1.3 x 10^8 BTU/y = 20 bbl/y

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Infiltration Energy Loss

$dQ/dt_{infil} = (dm/dt)\ c\ \Delta T$

dm/dt = infiltration rate of air mass, *c* = specific heat of air

R_{ACH} = 1/t ach (air exchanges/hour)
100% of interior air mass exhausted in $t_{residence}$ hours.

$dQ/dt_{infil} = (V\rho)\ R_{ACH}\ c\Delta T$

$V\rho$ = mass of interior air (volume x density).

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Annual heat energy needed over the year is

$dQ/dt_{infil} = (V\rho)\ R_{ACH}\ c\ (dd/yr)\ (24\ hr/day)\ /\ \eta$

$V = 2.5\ m \times 140\ m^2\ (8.2\ ft \times 1500\ ft^2)$
$R_{ACH} = 0.8$ ach
$\rho = 1.3\ kg/m^3\ (0.0735\ lb/ft^3)$
$c = 1004$ J/kg-°C (0.24 Btu/lb-°F)
dd/yr = 2800°C-day/yr (5000°F-day/yr)
$\eta = 2/3$

$dQ/dt = (140 \times 2.5\ m^3)(0.8\ ach)(1.3\ kg/m^3)$
(1004 J/kg-°C)(24 h/d)(2800 °C-d/yr)
$= 3.7 \times 10^{10}$ J = 35 MBtu/yr = 5 bbl/yr

Energy loss proportional to ach α **ach**
Bad health effects proportional $t_{residence}$ $t_{residence}\ \alpha\ 1/ach$

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Scaling Model of a Cubic Building

$dQ/dt]_{loss} = UA\ \Delta T = KL^2\Delta T$

$dQ/dT]_{gain} = FnL^2 = FL^3/H = GL^3$ (n = L/H)

F = 66 W/m^2 (6 W/ft^2), H = 3 m ➔ G = 22 W/m^3

$dQ/dt]_{gain} - dQ/dt]_{loss} = GL^3 - KL^2\Delta T_{free}$

$\Delta T_{free} = (G/K)L$

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Large Building:

$1.5L^2$	ceilings [R15, R_{SI}2.62], floors 50% of ceilings
$0.7 \times 4L^2$	70% walls [R6.5, R_{SI}1.14]
$0.3 \times 4L^2$	30% windows [R1, R_{SI}0.16]
x 1.3	infiltration

$K = (1.3)[1.5/2.62 + 0.7(4)/1.14 + 0.3(4)/0.16] = 14$

$\Delta T_{free} = (G/K)L = (22/14)L = 1.6\ L$

L=10 m (33 ft), = 16°C (28°F) [skin dominated]

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Multiple Savings

$dQ/dt]_{net} = dQ/dt]_{loss} - dQ/dt]_{gain} = KL^2[\Delta T - \Delta T_{free}] =$

$dQ/dt]_{net} = KL^2[\Delta T - (G/K)L]$

Reduced conductivity K saves by

- multiplicative KL^2
- subtractive $\Delta T_{free} = (G/K)L$
- degree-day distribution (some days save 100%, other days f%)
- Store day-time heat for cool evenings
- Save evening coolth for daytime air-conditioning
- infiltration can then dominate, use air-to-air heat exchangers
- "heat with two cats fighting" [Lovins], but economics enters

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Passive Solar Heating

Insulate before you *insolate*.

Glass plus Mass prevents you

from freezing your ….!

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H to He: $\Delta m/m = (4 \times 1.0078 - 4.0026)/(4 \times 1.0078) = 0.7\%$

$\Delta E_{sun} = \Delta mc^2 = (0.0071)(2.0 \times 10^{30}\ kg/\mathbf{10})(3 \times 10^8\ m/s)^2 = 1.4 \times 10^{44}$ J

Solar average power

$\mathbf{P} = \Delta E/\Delta t = (1.4 \times 10^{44}\ J/10^{10}\ y) = 3.9 \times 10^{26}$ W

Solar flux at Earth (1.37 kW/m²)

$S_o = P/4\pi(1\ AU)^2 = (4.4 \times 10^{44}\ W)/(4\pi)(1.5 \times 10^{11}\ m)^2$
$= 1.6\ kW/m^2$

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Solar flux absorbed, ΔS, in small air mass Δm:

$\Delta S = -\lambda S\ \Delta m,$

where λ is absorption constant. This integrates to

$S_1 = S_o\ e^{-\lambda m}.$

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Air mass increases with angle θ from zenith

$m = Nm_o = m_o \sec(\theta)$

where m_o is air mass at $\theta = 0^o$. Solar flux at angle θ,

$S_1 = S_o \exp[-\lambda m_o \sec(\theta)]$

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λm_o determined from flux above atmosphere (S_o = 1370 W/m^2) and at Earth's surface (S_1 = 970 W/m^2) when sun in zenith:

$S_1 = 970\ W/m^2 = 1370\ W/m^2 \exp(-\lambda m_o).$

This gives λm_o = 0.33 and solar flux at sea level ,

$S_1 = S_o e^{-0.33\sec(\theta)} = S_o e^{-1/3\cos(\theta)}$

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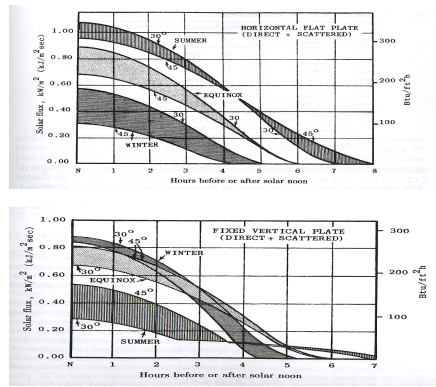

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SLO vertical window at noon on winter solstice ($\theta = 34^o + 23^o = 57^o$)

$S_{Vo} = [S_o \sin(57^o)]\ [e^{-1/3\cos(57)}] = [435][0.84][0.542]$

$= 200\ Btu/ft^2\text{-}hr$

Integrated solar flux over a day:

$I = \int_0^{T/2} S_V\, dt = \int_0^{T/2} S_{Vo} \sin(2\pi t/T)\, dt = S_{Vo}T/\pi$

$= 200 \times 20/\pi = 1280\ Btu/ft^2\text{-}d$

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Winter window gains and losses: (San Luis Obispo)
single-glaze [U = 1 Btu/ft^2-hr]
50 °F outside temperature
90% transmission through
flux, south-facing,
$S_V = [270\ Btu/ft^2hr] \sin(2\pi t/T)$, T/2 = 10 hour

Heat loss:

$Q_{loss}/A = U\ \Delta T\ \Delta t = (1)(65\ °F - 50\ °F)(24\ hours) =$
$= 400\ Btu/ft^2\text{-}d$

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Solar gain:

$Q_{gain}/A = 0.9I = (0.9)(1300\ Btu/ft^2\text{-}d) = 1150\ Btu/ft^2\text{-}d.$

$Q_{gain}/Q_{loss} = 1150/400 = 3$

Improvements:

- drapes or R-11 venetian blinds at night
- double-glaze, low-E windows (R4).

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Thermal Flywheel House

A tank of water 25 cm thick is "optimal."
Ignore small temperature variations over the volume .

$Q = mC\ \Delta T,$

- m is water mass
- C is specific heat
- ΔT is temperature difference between the tank and room

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Heat loss rate from tank volume:

$dQ/dt = mC\ dT/dt$

Heat-loss rate from surface:

$dQ/dt = AU_{total}\Delta T$

- A = tank area (m^2)
- $U_{total} = U_{convection} + U_{radiation} = 12\ W/m^2$
- $\Delta T = T_{barrel} - T_{room}$ = T above room temperature

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Equating surface loss rate to volume loss rate:

$dQ/dt = AU_{total}T = -mC\ dT/dt,$

gives:

$T = T_o\ e^{-t/\tau}$ and $\tau = mC/AU_{total}$

A 25-cm thick tank on a square meter basis:

$\tau = mC/AU_{total} =$
$= (250\ kg)(4200\ J/kg\text{-}^oC)/(2\ m^2)(12\ W/m^2\text{-}^oC) = 12\ hr$

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