PHYS-310: Energy, Society, and the Environment
180-265

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

DH:
3) Buildings

Folks in the physics department are making a fuss about the fastest, most expensive production car in the world, Bugatti Veyron. Here's the video: http://www.youtube.com/watch?v=LO0PgyPWE3o Then you can read about it in Wikipedia, or any place else you can find that interests you. You can skip down to the statistics if you like. At its maximum speed we can presume that it puts out its maximum power, find the efficiency:
a) Look up the maximum power that the engine puts out (please give answer in HP and Watts). What form of energy is this?
b) How does this power compare to a regular car? What is the max power (in HP and Watts) of your car?
c) What is the rate of consumption of petroleum at maximum power output?
d) What is the (chemical potential) energy consumption rate? Please put answer in Watts.
e) What is the efficiency of the gasoline engine at maximum power?
f) What rate (in Watts) does the engine dissipate heat? How many 100W light bulbs would this be? Why would this car need 10 radiators?

Environment:
g) How much $CO_2$ does the car put into the atmosphere in one second? And how much does it put into the atmosphere in the 12 minutes it can drive at top speed before running out of gas? Please put answers in kg of Carbon, AND kg of $CO_2$.

Demographics: You may not be able to find the exact information you are looking for below. Don't sweat it… Please innovate an answer that makes sense to you.
h) If a group of people in the following countries wanted to buy a Veyron, and saved half of their salary for a year, how many people would they have to get together?: USA, Guatemala, DR Congo.
i) About what per cent of people in the following places could afford a Veyron?: USA, Guatemala, DR Congo. Assume that the person had to be an Ultra Millionaire (worth more than $30 million). Site your sources.

# Physics of Buildings

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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-$^o$F = 1 Art (Henry Kelly)
(W/m$^2$-$^o$C)

Steady state heat transfer is similar to DC circuits

| | | |
|---|---|---|
| V = | I | R |
| $\Delta T$ = | 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

$\Delta T_{free}$ =(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): $\Delta T_{free}$ = 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** $\alpha$ **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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**$\lambda m_o$ 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 $\lambda m_o$ = 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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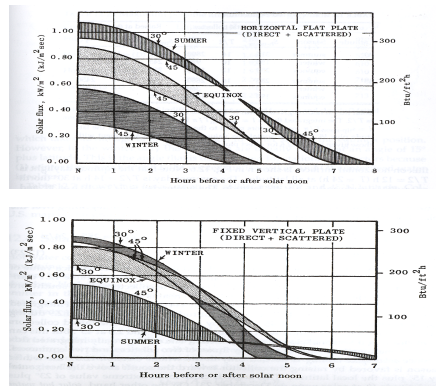


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**SLO vertical window at noon on winter solstice ($\theta = 34^o + 23^o = 57^o$)**

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

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

**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
- $\Delta T$ 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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