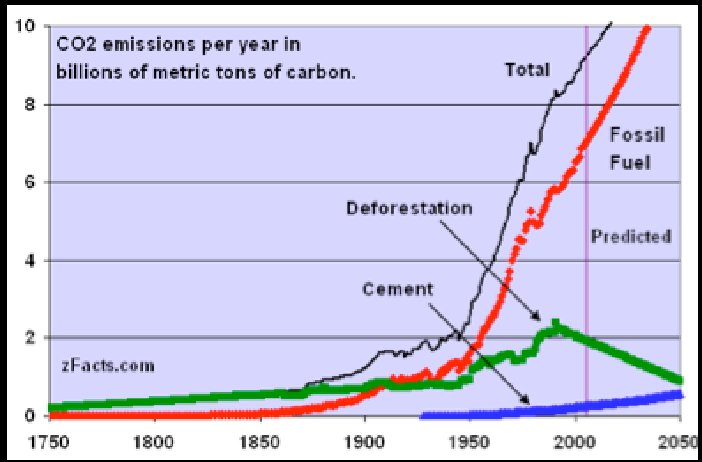

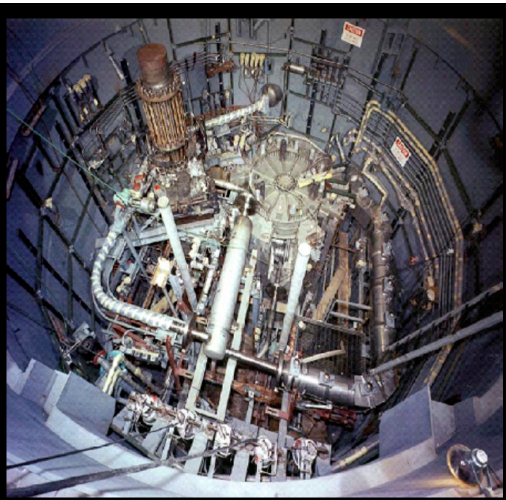

Climate Change and Energy Solutions

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Academia Sinica

10 August 2010

Wu Chien Shiung Science Camp

Collaborator: M. J. Cai

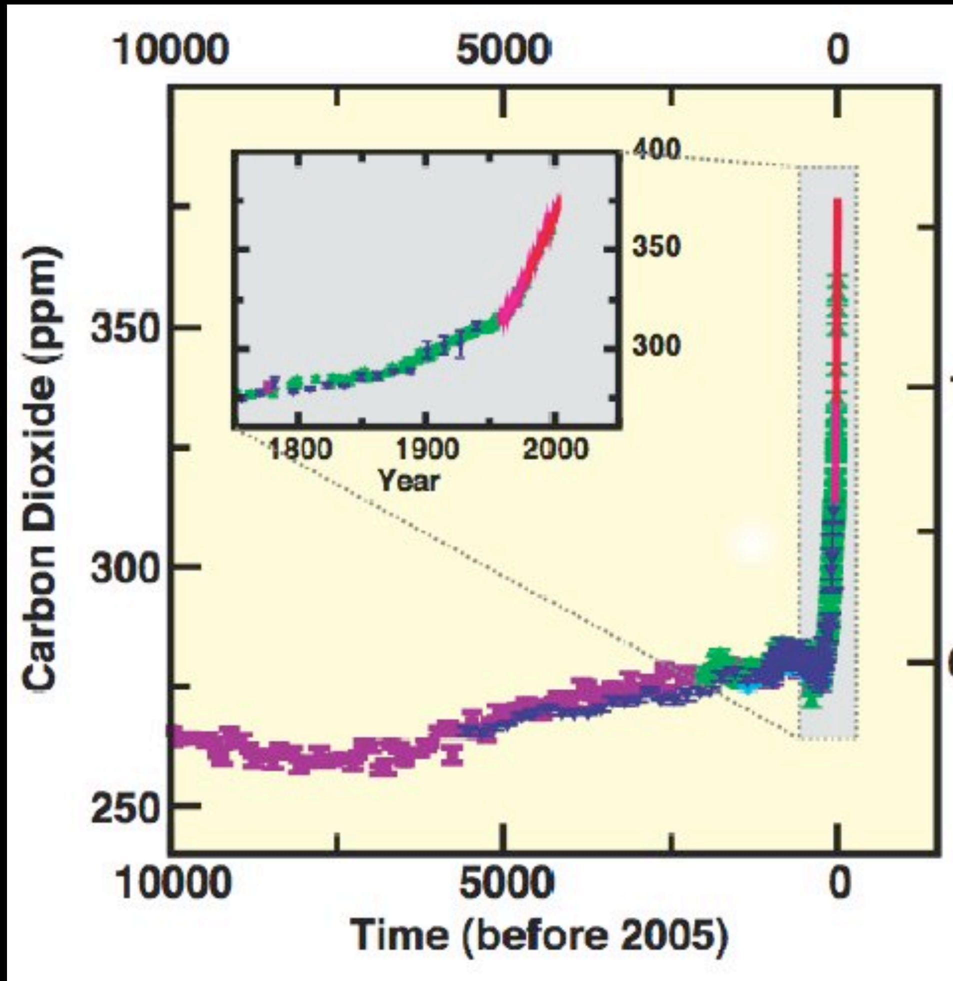
Outline of Presentation

- Basics of Climate Change
- Pacala & Socolaw, 2004, Science, 305, 5686, 968-972.
  - 450 ppm in 2050: 11 stabilization wedges (2 TWt or 1 TWe each)
  - Only five realistic choices:
    - Fossil fuel with CCS — expensive and difficult
    - Biofuel — necessary, but difficult at industrial scale
    - Solar PV/solar thermal — very expensive
    - Wind — not enough and many drawbacks
    - Nuclear — needs reprocessing and breeding
- Transformative technology: MSRs
  - Review of fission fuel cycles
  - Breeder reactors: SFR (fast n spectrum, U-238/Pu-239) and MSR (epithermal n spectrum, Th-232/U-233)
  - Waste management, passive safety, proliferation resistance, economics with new materials (carbon/carbon composites)
- Nuclear power to make artificial coal

Grand Challenge of 21st Century

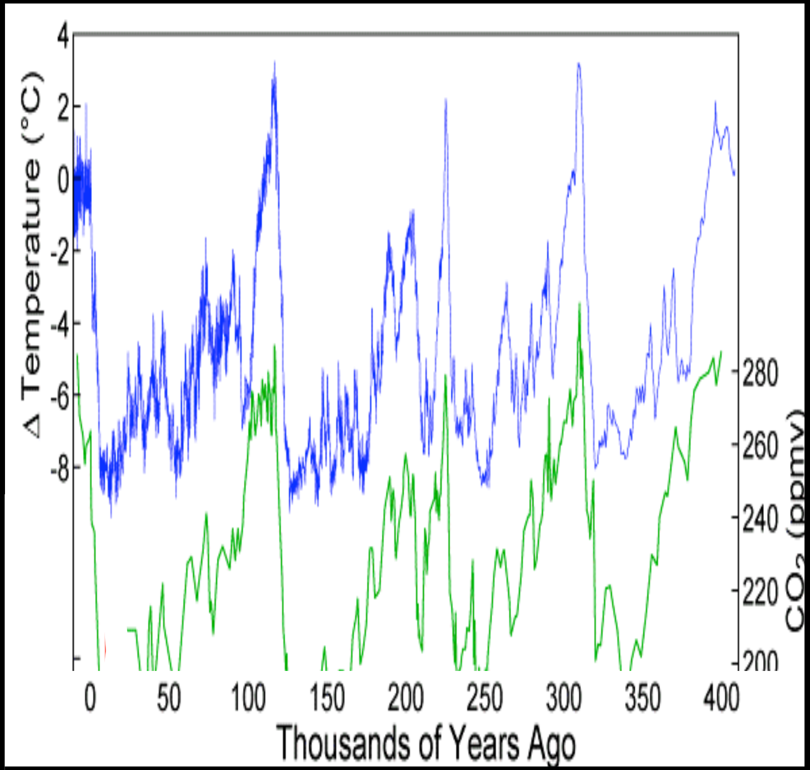
- Attributed to John Maynard Keynes:

  "For millennia, until the discovery of fossil fuels, the only way humans made economic progress was to enslave other peoples."
- According to James Hansen, tipping point for melting of polar ice is 350 ppm CO_2, which we passed in 1988.
- Why should we care?



Essence of Runaway Greenhouse Effect

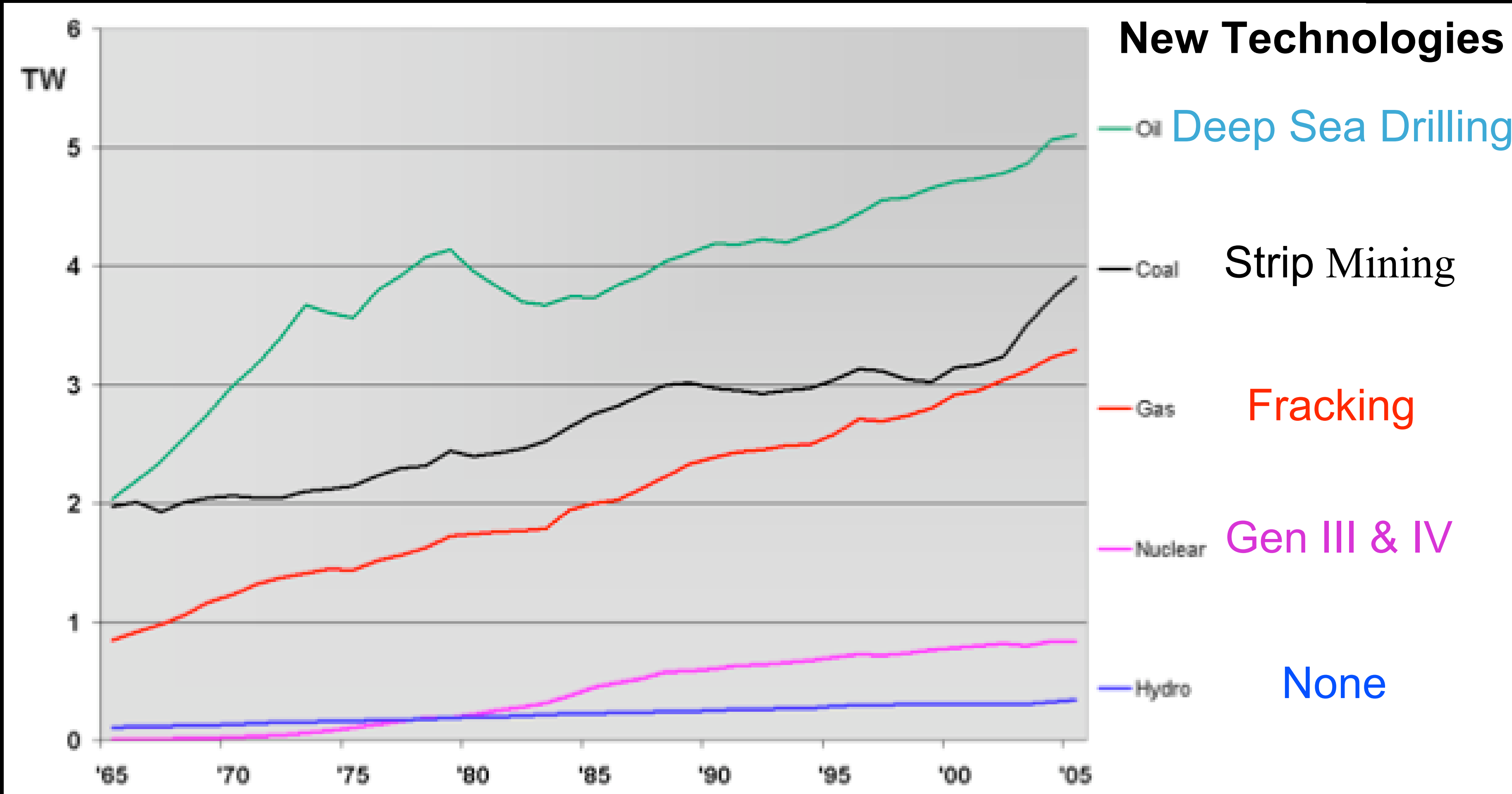
- Effective T of Earth:
  $T_E = (1\text{-}A)^{1/4} (R_E/2r_E)^{1/2} T_S$.
- For $A = 0.3$, $T_E = 255$ K.
- $T_g = T_E(3\tau/4+1/2)^{1/4}$.
  For $\tau = 1.72$, $T_g = 295$ K.
- Problem (nonlin feedback):
  – CO_2 increases τ & T_g.
  – Increase T_g melt polar ice.
  – Melt polar ice, decrease A, which increases T_E, which increases T_g.
  – Melt polar ice, eliminate latent-heat buffer, which increases T of oceans, which releases more CO_2 & water vapor.



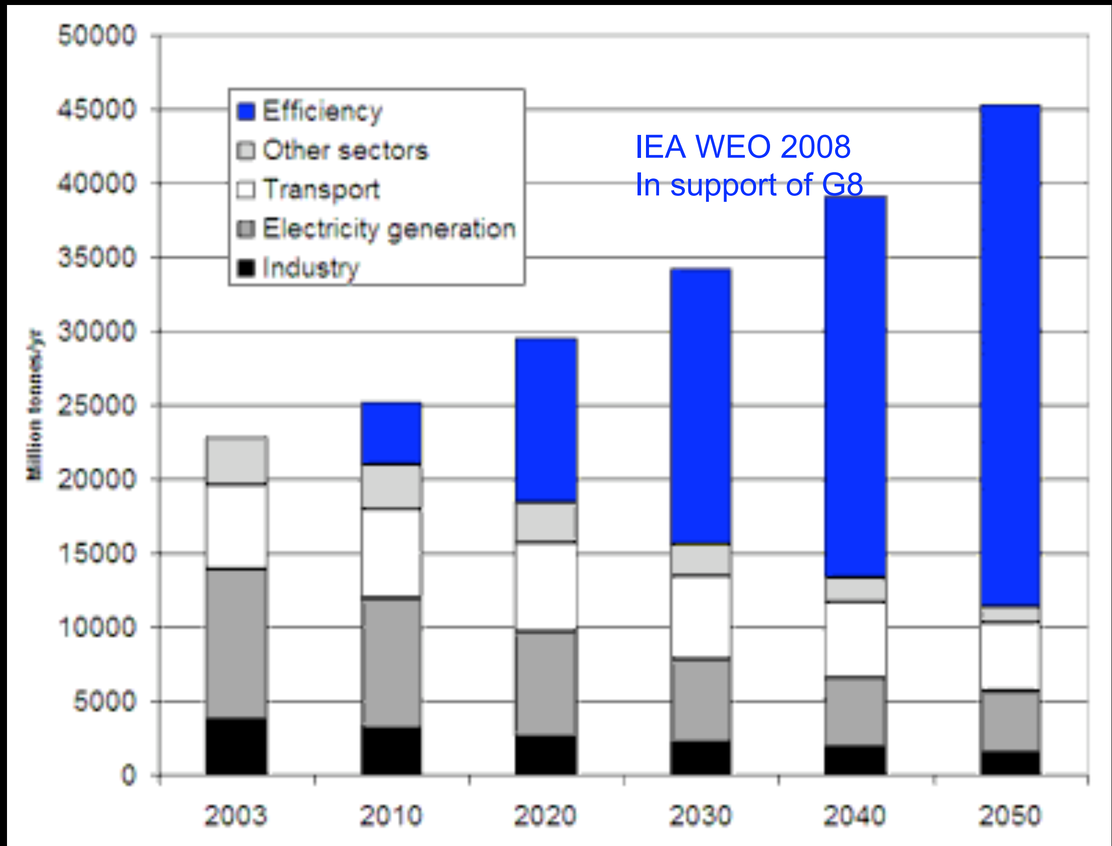
Milankovich cycle

At 200 ppm, 14,000 yr ago, Asians could walk to America. At 280 ppm, oceans rose eliminating this option. How much will the oceans rise at 450 ppm?

Trends in Energy Usage

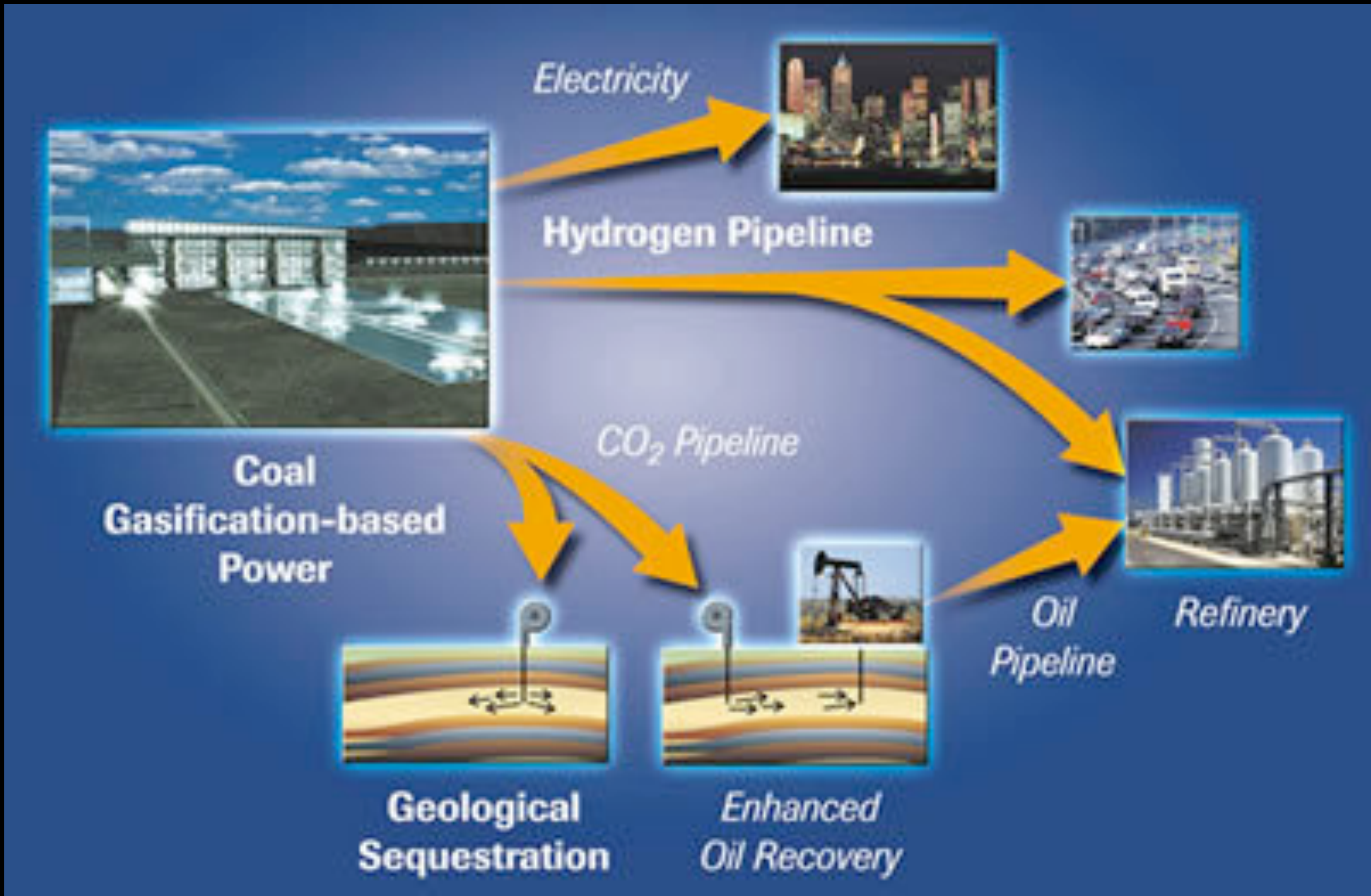


Energy Needs



Power requirement 30 TWt for entire world by 2050. A reasonable target for Taiwan is to lower current level to 90 GWt = 45 GWe. Only nuclear energy or solar PV can reach these targets without massive damage to the environment. Current energy policy in much of world = wishful thinking.

Fossil Fuel with CCS



Capture adds 30-60% extra cost; sequestration, double?

Depleted oil wells & coal mines not enough room

Existing plants not necessarily at appropriate sites

Capture as $CaCO_3$ in flue gas may be better option

FutureGen canceled under Bush for cost overruns; resurrected under Obama

Biofuel

Solar energy falling on land:

$$(0.3)(0.7)\left(\frac{L_\odot}{4\pi r_E^{\,2}}\right)\pi R_E^{\,2} = 37{,}000 \text{ TW}$$

averaged over latitude, day / night, & seasons.

Efficiency of land plants like corn = 0.1%, 3 TWt for t, t, b, j; need 8% of all land.

Better strategy: reactor heat to make BioSyn and biocoal from corn stover.

Even better, bamboo (0.7% eff), but 3 x Taiwan to support all its transportation & coal-fired plants (need partnership).

Solar Photovoltaics

Solar energy falling on land:

37,000 TW

averaged over day/night & seasons

Stadium in Kaoshiung, Taiwan

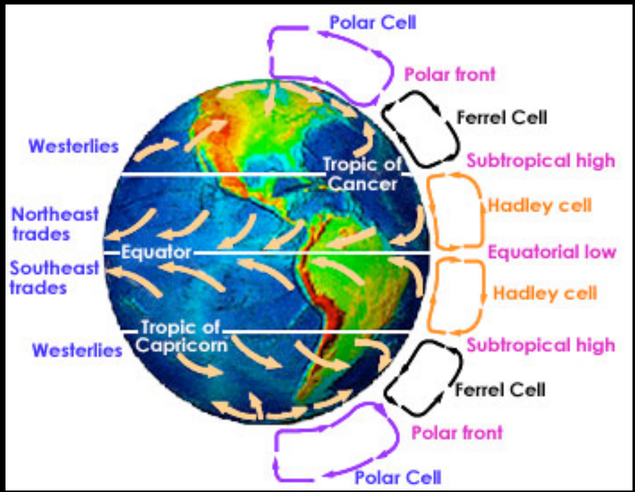
Efficiency of best solar cells = 20%; 0.2 x 37,000 TW = 7,400 TWe. For 15 TWe (total world energy need), devote 0.2% of land to photovoltaics (1/15 of world's urban area). Rooftops generally insufficient; need windows too.

Land area is not a problem, even for Taiwan (5% of all land). Big problem is cost: 0.20 USD per kWh = 4.5 x coal. Taiwan target for PV: 1 GWe.

Even then, problem is intermittency -- sometimes (esp. in Taipei), it is cloudy.

Solar thermal needs 10 x land of solar PV. Cost ~ 0.12 USD per kWh without storage, maybe double if store heat (e.g., as molten salt, easier than storing electricity).

Wind Power



Wind farm in Horns Rev, North Sea

Uneven solar heating = heat engine & wind:

$$\text{Max eff} = \frac{T_g - T_E}{T_g} = \frac{295 - 255}{295} = 0.14.$$

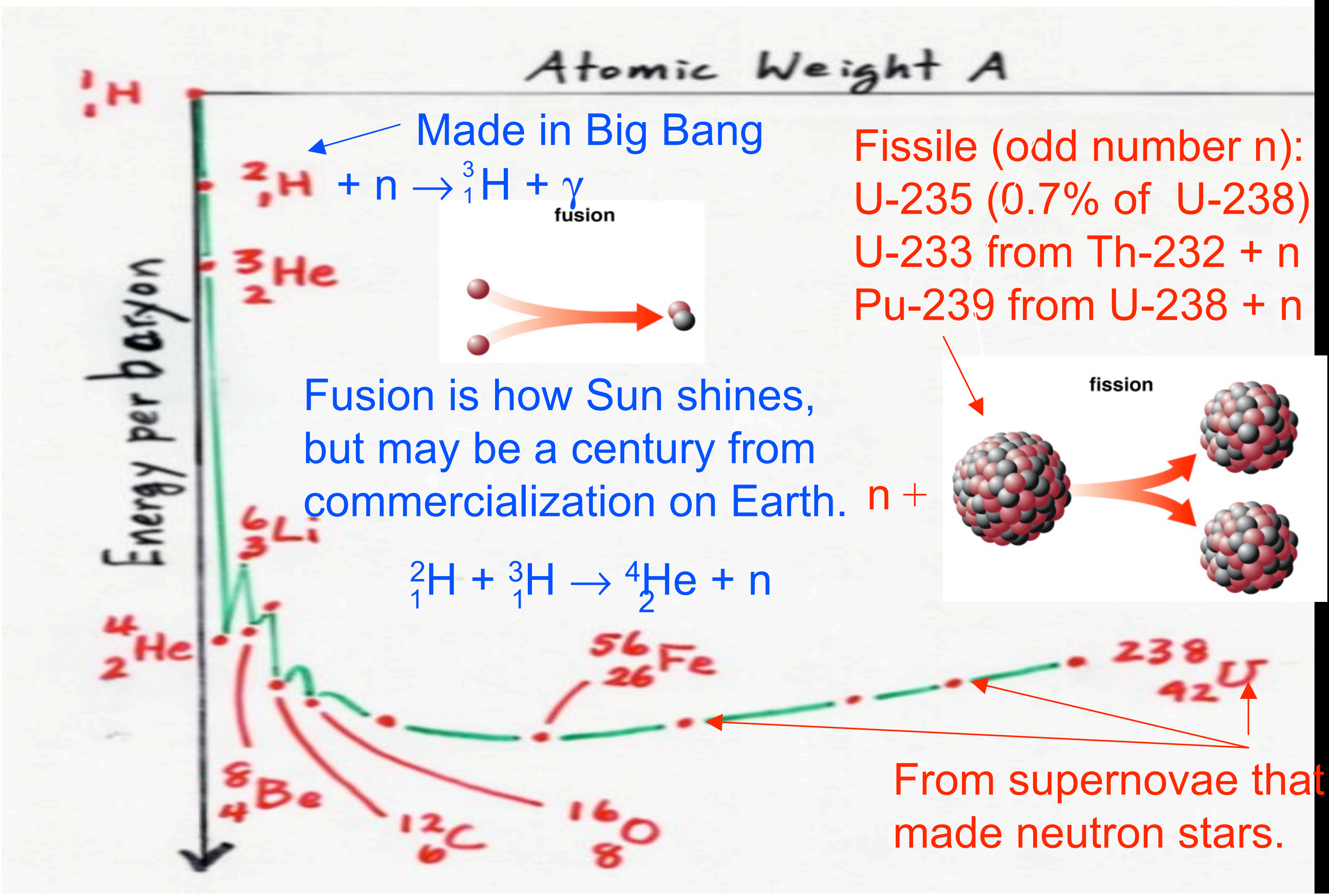
0.14 x 37,000 TW = 5,000 TW. Kinetic energy extends over 8 km height of atmosphere, giving average wind speed of 25 m/s if renewed every 24 hr. If diameter *D* of turbine blade is 80 m, only tap 1% of total = 50 TW. At favorable location, wind speed at hub height = 7 m/s; reduce by $(7/25)^2$; get 4 TW. Conversion efficiency (50%) to electric power nets 2 TWe. Much smaller than 72 TWe at favorable locations (13%) estimated by Archer & Jacobson (2005) who ignore "shadowing" & drag in 4*D*x7*D* spacings.

German experience (DENA 2004): aim for load = 30% of capacity ~ 0.10 USD per kWh > 2 x coal. Taiwan target: 3 GWe offshore.

Renewables vs. Nuclear

- Collecting, distributing, and storing *dilute* sources of natural energy goes against the *concentrated* way that most people now live in cities.
- Nuclear energy contained in 1 kg of uranium or thorium is *2.3 million times* that contained chemically in 1 kg of coal. Not to be dismissed out of hand.

Nuclear Power: Fusion & Fission



Th is 3 to 4 times more abundant in Earth's crust than U.

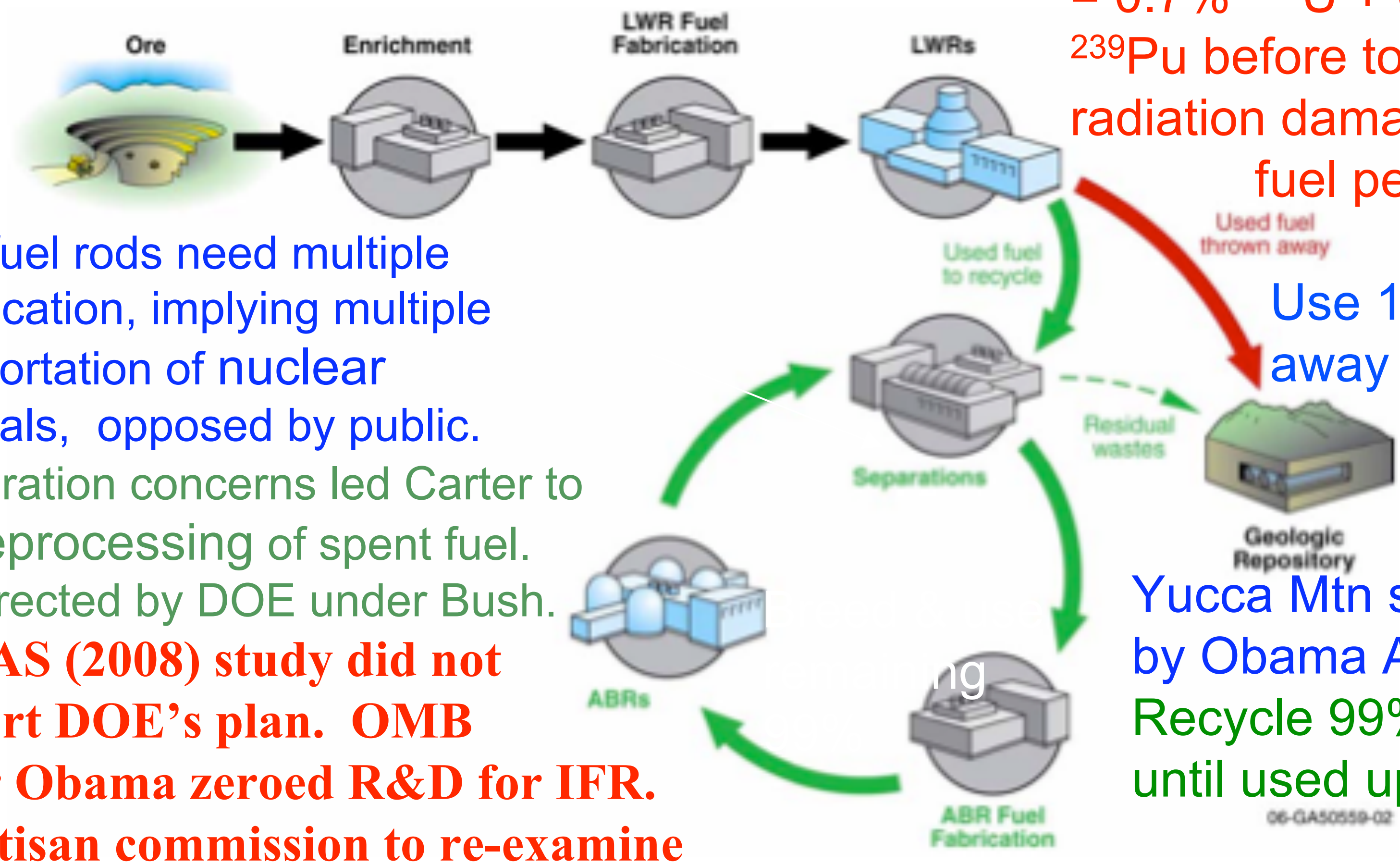
\+ 2 or 3 n

\> 1 chain reaction

\> 2 breed

Reactor: sub wrt prompt n, super wrt delayed n

Nuclear Energy: Reprocessing & Breeding



LWR efficiency = 1% = 0.7% ^{235}U + 0.3% ^{239}Pu before too much radiation damage of fuel pellets

Use 1%,throw away 99%.

Solid fuel rods need multiple refabrication, implying multiple transportation of nuclear materials, opposed by public.

Proliferation concerns led Carter to ban reprocessing of spent fuel. Resurrected by DOE under Bush.

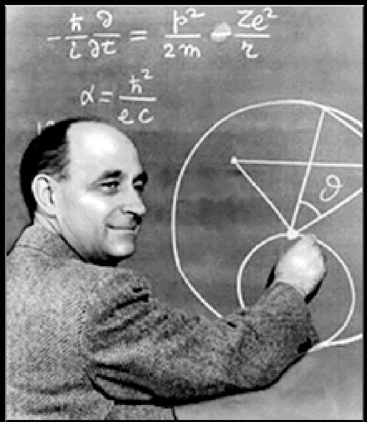
US NAS (2008) study did not support DOE's plan. OMB under Obama zeroed R&D for IFR. Bipartisan commission to re-examine reprocessing & report in 2012.

Yucca Mtn stopped by Obama Adm

Recycle 99% until used up.

Tale of Two Cycles

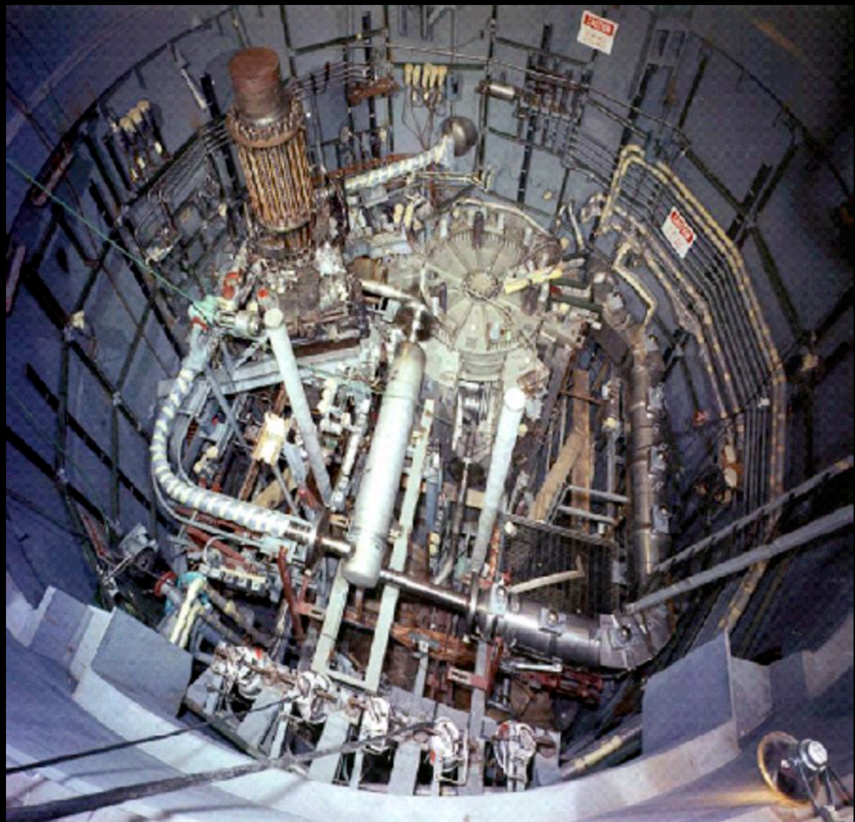
$^{238}\mathrm{U}(n,\gamma)^{239}\mathrm{U}(e^-\bar{\nu}_e)^{239}\mathrm{Np}\ (e^-\bar{\nu}_e)^{239}\mathrm{Pu}$



$^{232}\mathrm{Th}(n,\gamma)^{233}\mathrm{Th}(e^-\bar{\nu}_e)^{233}\mathrm{Pa}\ (e^-\bar{\nu}_e)^{233}\mathrm{U}$

- Fermi’s objection to thorium cycle: Pa-233 with half-life of 27 days, has a fairly large cross-section for additional n-capture. Wastes n in creating U-234, and breeding ratio drops below 1.
- Wigner’s answer: build a *liquid-based* reactor, and chemically extract Pa-233 on a short time scale (e.g., a week) before it has a chance to decay.
- Have to start with U-235, which comes with U-238, so Fermi’s view prevailed; world followed US lead, which resulted in today’s (mis)perceptions of nuclear power: unsafe, expensive, difficult waste disposal problem, with close connection to WMD.

MSRE

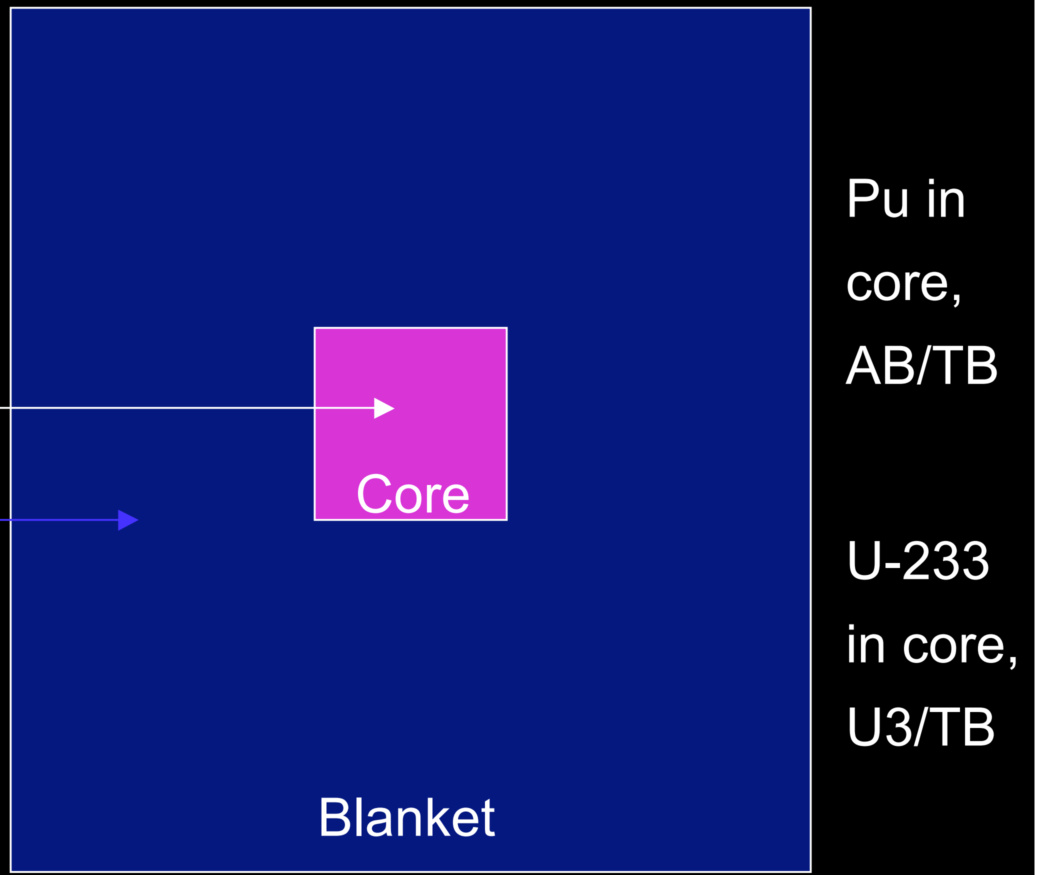


- Built by ORNL in 1960s, originally in response to US Air Force desire for nuclear powered airplane (cancelled)
- Never applied to civilian power generation:
  - Destroys Pu (does not make it)
  - Fuel fabrication not needed
  - Complete burnup if Th-232/U-233 is adopted fuel cycle
  - Thermal breeder competitor to fast sodium reactor

Two-Fluid MSRs Can Rid LWR Waste & Safely Breed for U-233

Chain reaction, breeding, and processing done in liquid medium of molten salt

- LWR spent fuel
  - U-235, U-238
  - Fission prod’s
  - Pu/actinides
- Th-232



Enough Th-232 in Lehmi Pass for 2,000 yr of USA energy use.

Carbon-Carbon Composite

- Graphite used since dawn of nuclear age for n moderation
- C/C composite = engineered graphite: graphite matrix (from coal tar pitch) + carbon fiber fabric
- Reaction bonded above 2500 C; coat (CVD with ethylene) to reduce permeability
- High thermal conductivity or insulation (depending on fiber orientation); high strength (greater than steel, but vulnerable to sharp blows); nearly zero CTE (leak resistant)
- Expensive, 100 - 4,000 USD/kg (can use lower cost material for first MSRs)

Two-Fluid MSR

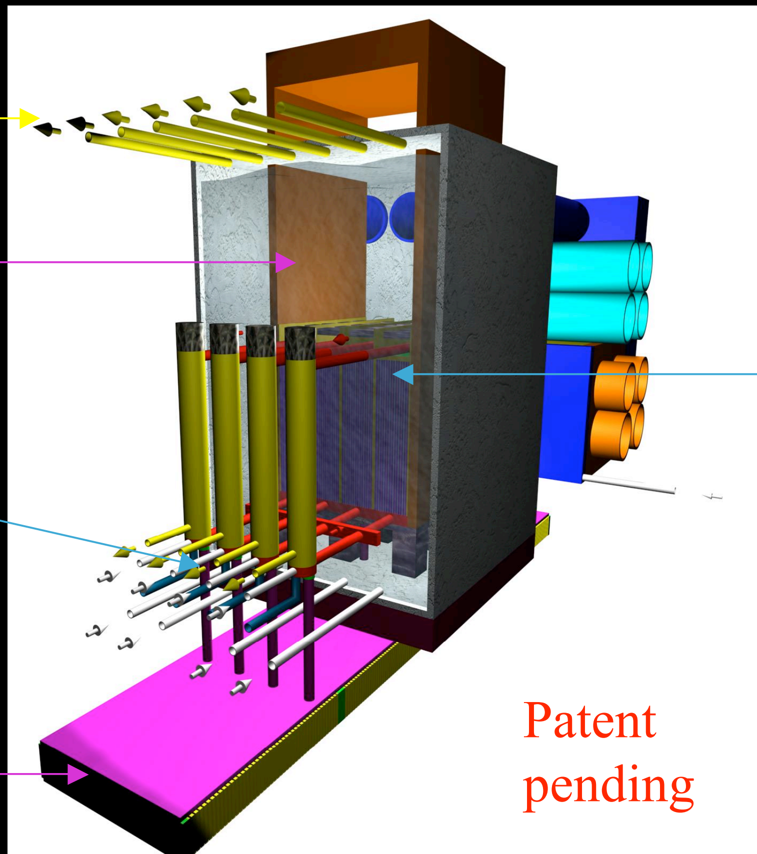
Except for dump tank, system built from C/C composites, resistant to chemical corrosion by molten fluoride salts

He purge of gaseous Xe-135

Active/passive control

Passive safety feature 3: If *T* still rises, solid plug melts, & fuel salt drains into (cooled) dump tank.

Air-cooled dump tank to remove decay heat; cannot lose air coolant



Passive safety feature 2: Fuel salt expands out of reaction zone if over-heated.

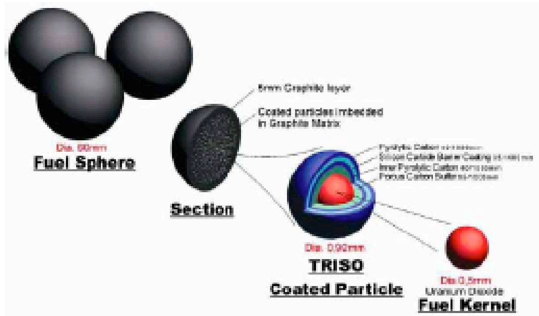
Breeding ratio for U3/TB can be as high as 1.12 without extracting Pa-233 (diluted in large blanket/pool).

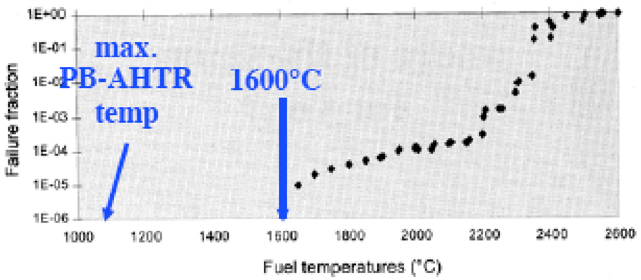
Molten salt, low vapor pressure. Fuel molten: no radiation damage, circulate until 100% burn-up, no meltdown, no TMI. Double-walled outer containment, no Chernobyl nor jet crashes. Burn Pu; U-232 accompanies U-233; no bombs.

Best Choice for Taiwan: Berkeley-ORNL PB-AHTR

Advanced High-Temperature Reactors (AHTRs) combines two older technologies

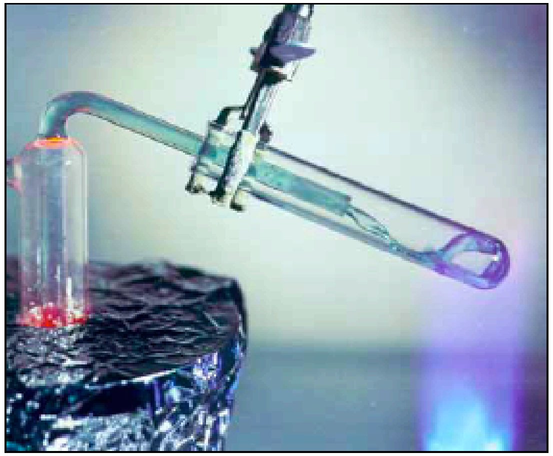
Coated particle fuel





Fuel performance chart (Source: PBMR [Pty] Ltd.)

Fuel failure fraction vs. temperature

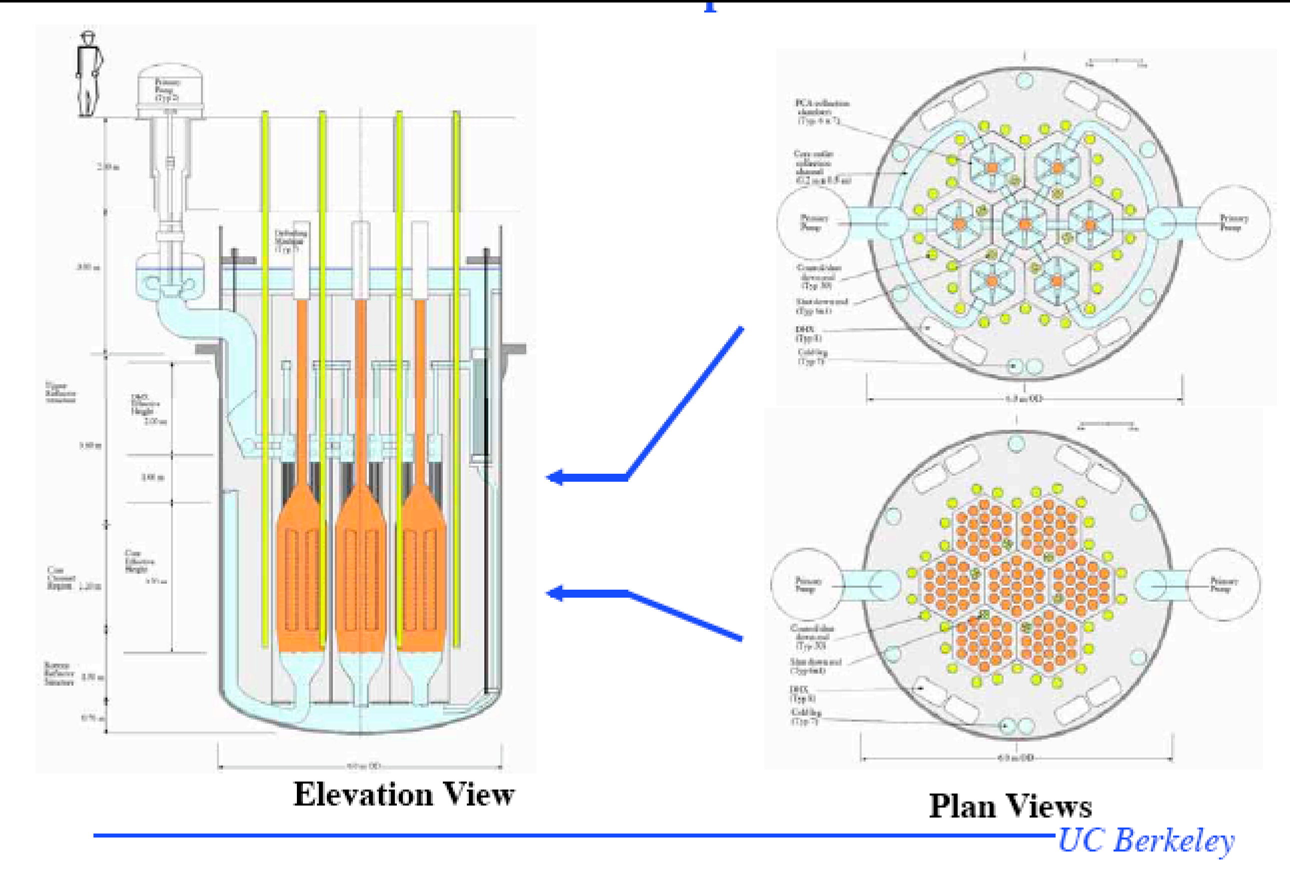


Liquid fluoride salt coolants

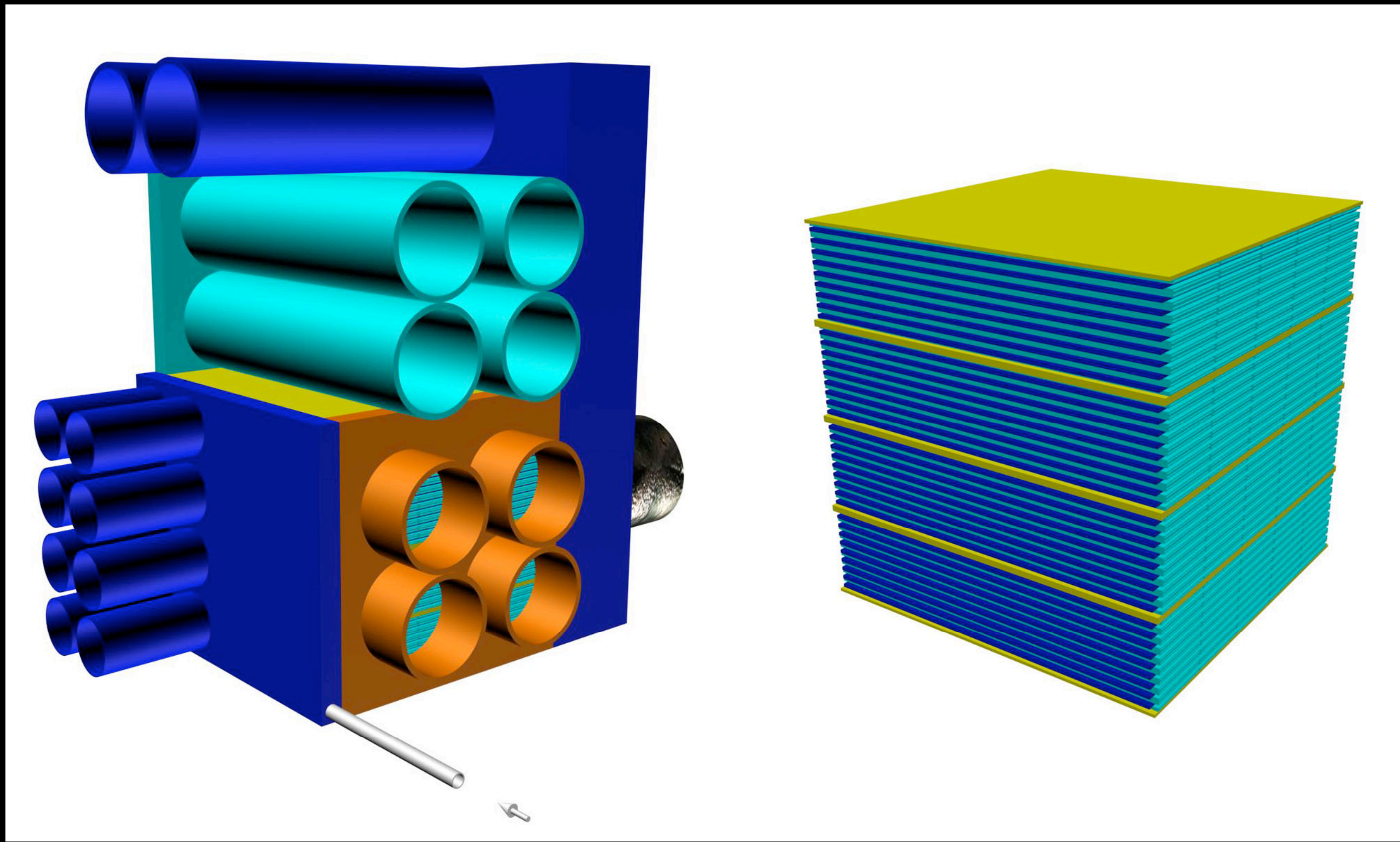
Excellent heat transfer
Transparent, clean fluoride salt
Boiling point ~1400°C
Reacts very slowly in air
No energy source to pressurize containment

UC Berkeley

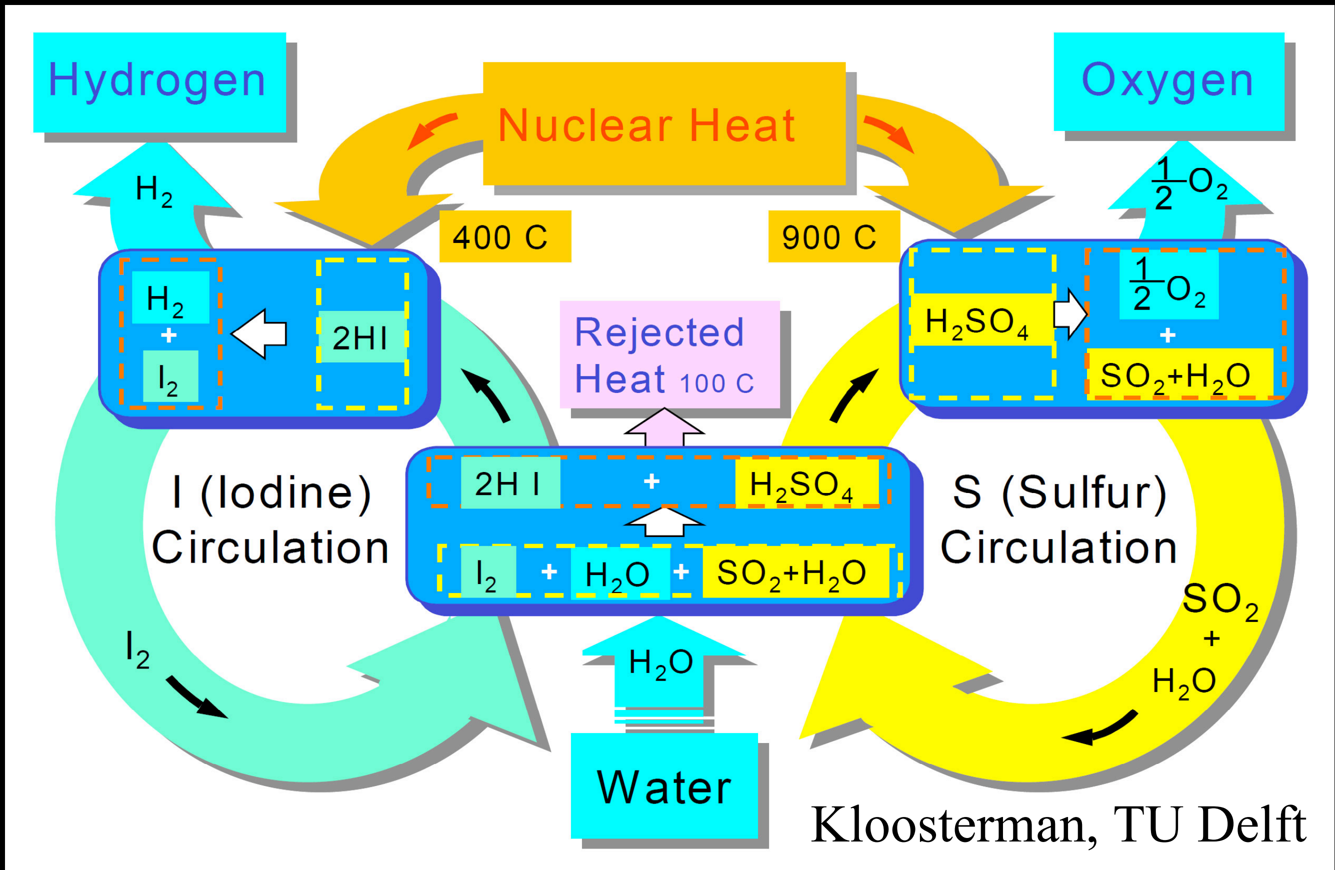
Modular PB-AHTR Channel Assemblies



Proposed Taiwan Contribution: Compact Heat Exchangers



Application 1: Thermal-Chemical Dissociation of H_2O



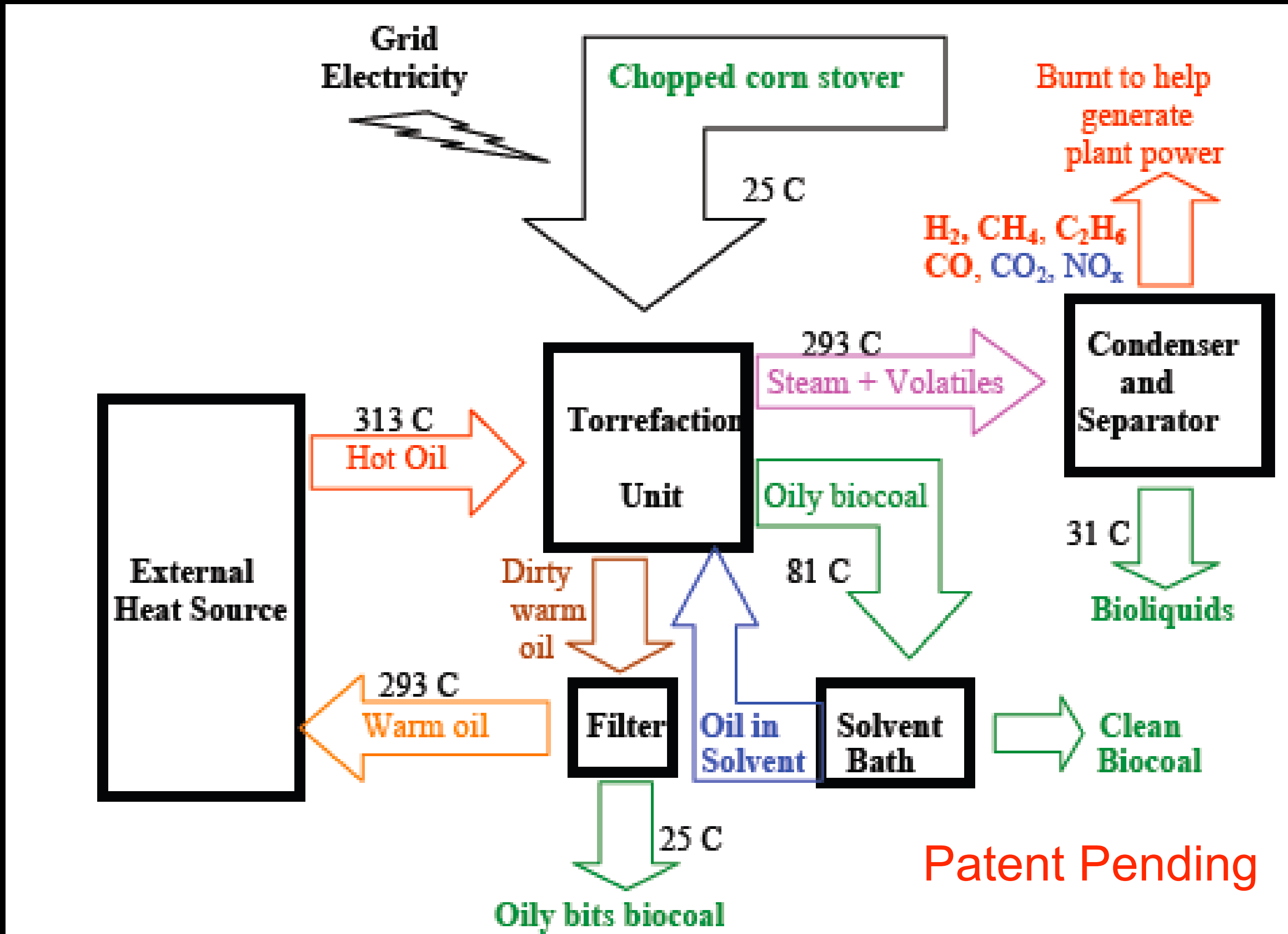
Application 2: Artificial Coal

Capture ratther than burn condensable volatile organic compounds: high throughput pathway to making liquid and gaseous biofuels.

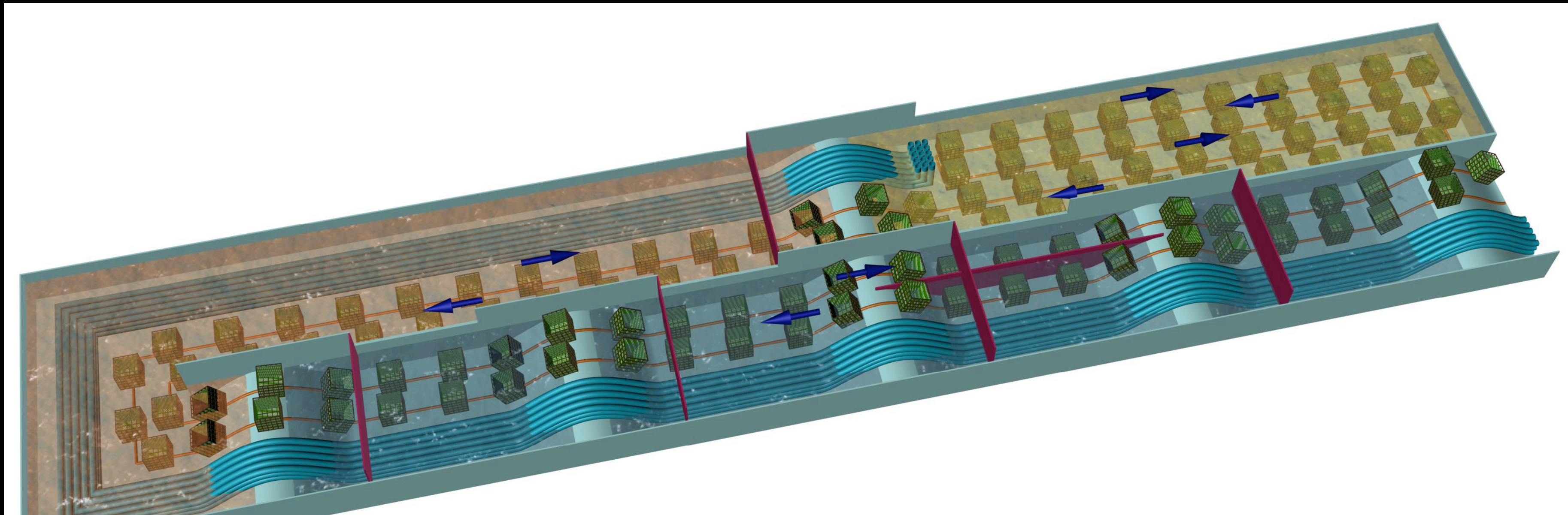
Learn from nature

AS Chemistry Institute: F. T. Luo

Schematic Steps to Making Biocoal

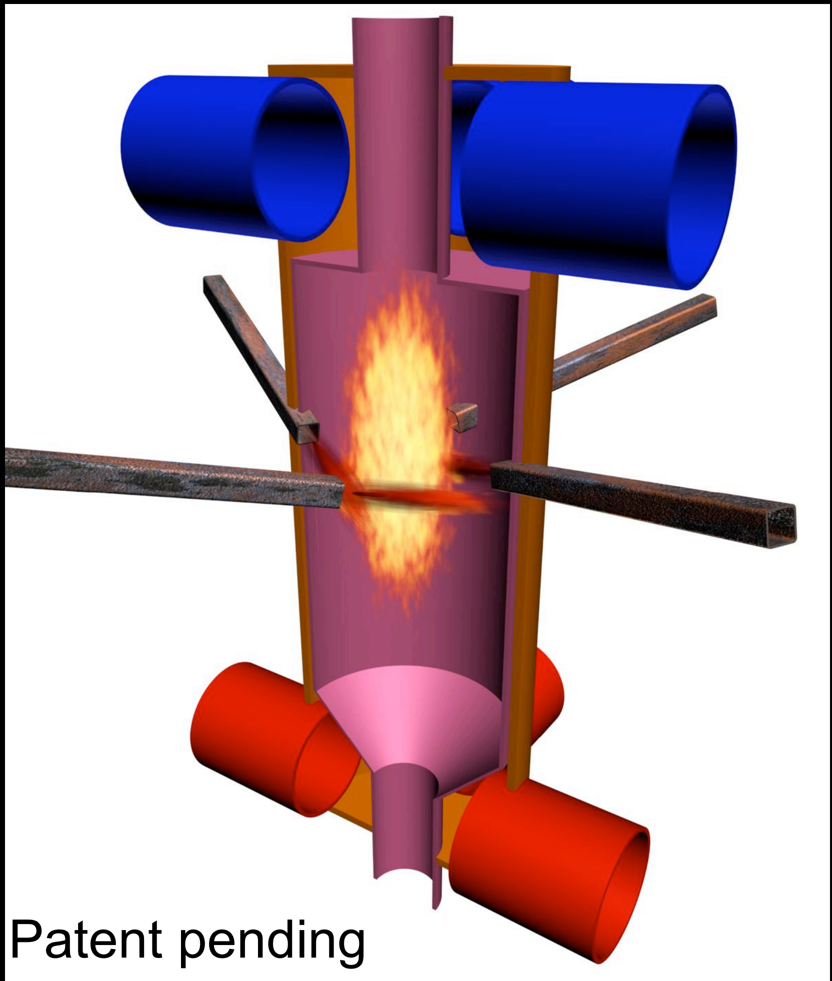


Practical Implementation of Torrefaction Facility



Patent Pending

Biofuel Breeder: Biocoal-Burning Furnace



Pilot project: powered with biocoal-fired furnace.

Produce 80 tonnes biocoal per day, enough to sustain campus or city of 50,000 with zero CO_2 emission.

Estimated cost: 10 MUSD/3 years = 200 USD per person/3 yr = 6,000 NTD/3 yr.

Summary

Botticelli: Spring, painted during the Italian Renaissance

- Saving human civilization through a nuclear renaissance is still possible, but only if environmentalists and nuclear activists stop fighting.
- Please help by learning about climate change and realistic energy solutions, and not let misinformation dominate the public discourse.