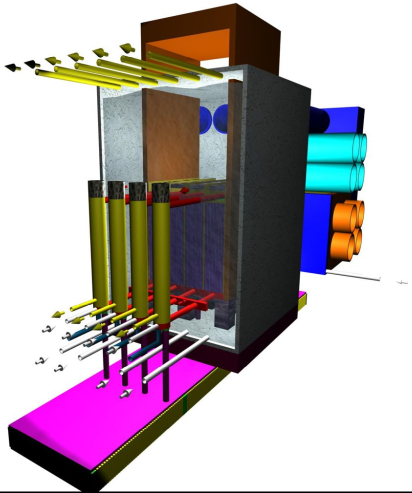
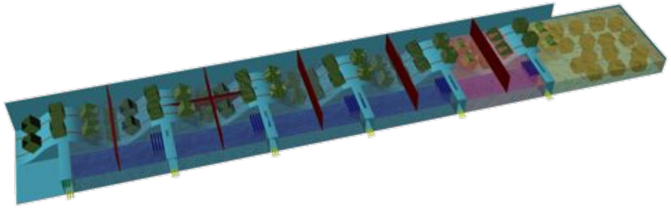
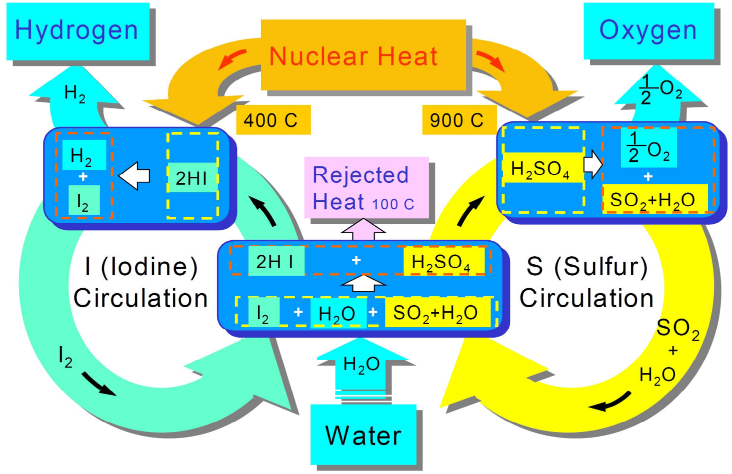






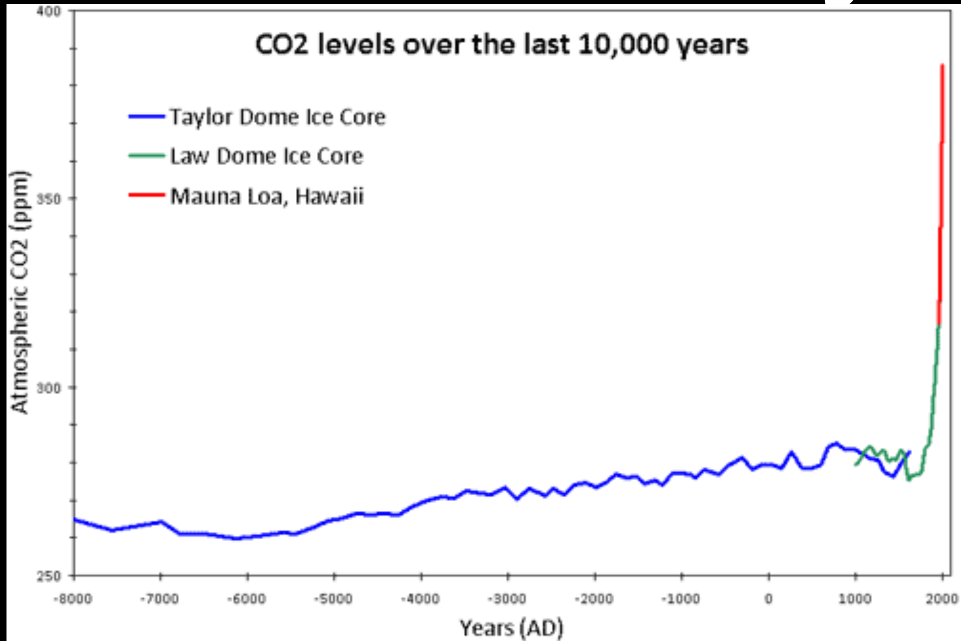

# Climate Change and Energy Solutions

Frank H. Shu
UCSD, Academia Sinica, U Michigan

24 January 2011

Geological and Planetary Sciences
Caltech
Collaborators: M. J. Cai, F. T. Luo, HX Team

# Grand Challenge of 21st Century

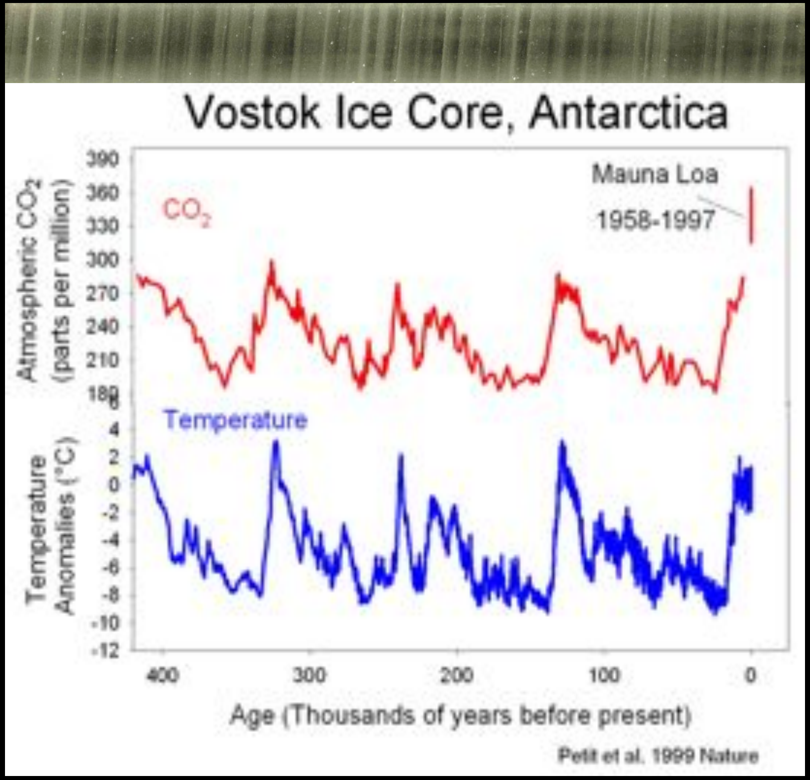



"For millennia, until the discovery of fossil fuels, the only way humans made economic progress was to enslave other peoples." (attributed to John Maynard Keynes)

- According to James Hansen, tipping point for melting of polar ice is 350 ppm $CO_2$, which we passed in 1988.

# Essence of Global Warming

- Effective $T$ of Earth:
  $T_E = (1\text{-}A)^{1/4}\,(R_S/2r_E)^{1/2}\,T_S$.
- For $A = 0.3$, $r_E = 215\ R_S$, $T_S = 5{,}800$ K, $T_E = 255$ 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 $\tau$ & $T_g$.
  - 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 America. At 280 ppm, oceans rose eliminating this option. How much will the oceans rise at 450 ppm?

# US Electricity Generation

| USA 2008 Electricity DOE | Nameplate Capacity | Capacity factor |
|---|---|---|
| Coal | 337.3 GWe | 0.722 |
| Natural Gas | 454.6 GWe | 0.407 |
| Petroleum | 63.7 GWe | 0.092 |
| Nuclear | 106.1 GWe | 0.911 |
| Hydro | 77.7 GWe | 0.372 |
| Wind | 25.0 GWe | 0.3 |
| Solar | 0.5 GWe | 0.2 |

US added only 1% & 0.01% capacity in wind & solar in 30 yr. Reasonable goal for US: hold to capacity of 3700 GWt = 1,850 GWe, without massive damage to environment & without undermining nation's competitiveness.

# Coal vs. Renewables vs. Nuclear

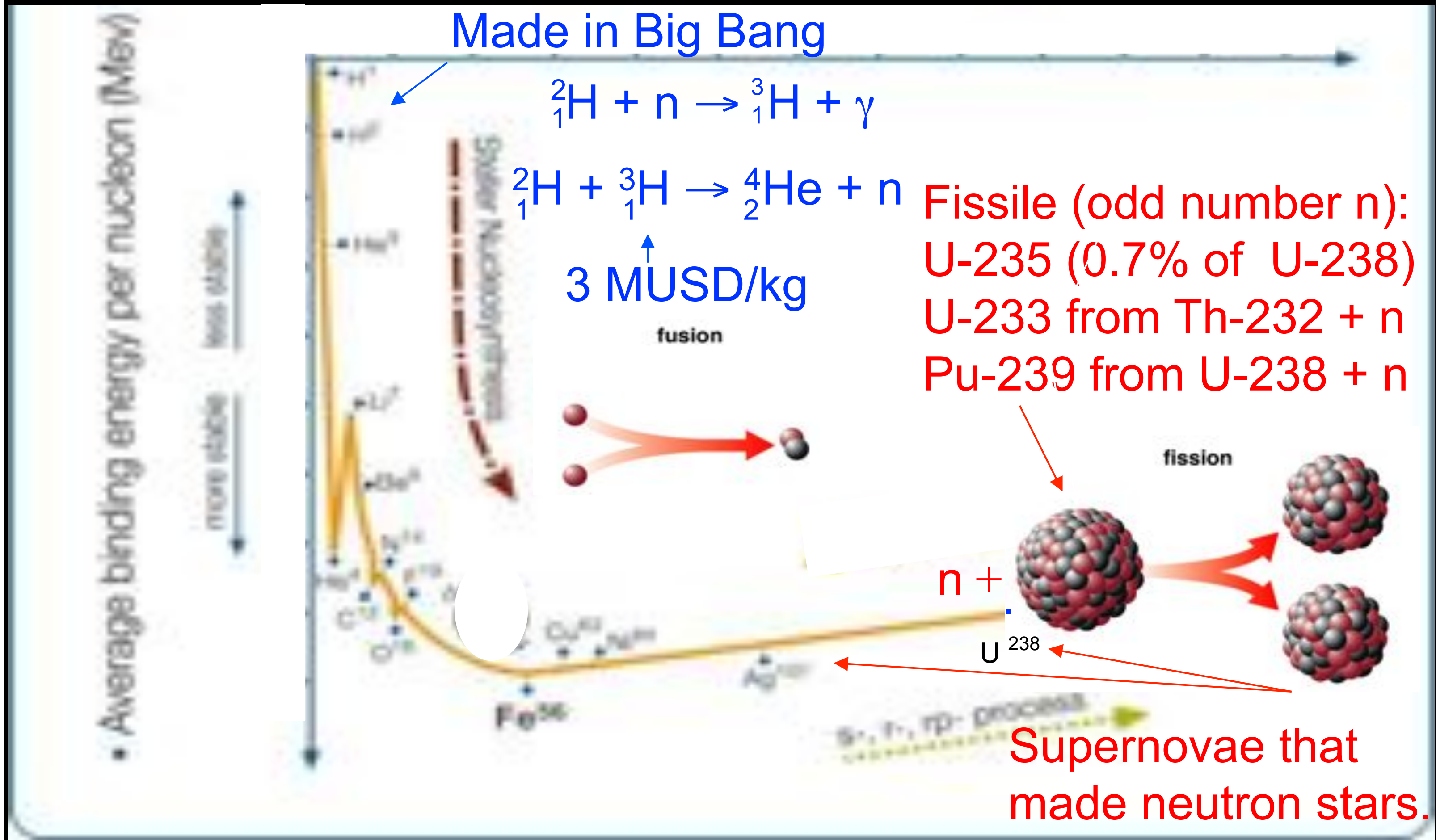
- Coal is a very *concentrated* form of chemical energy – 50x Li ion battery per kg.  Latter can be recharged ~ 500 times, but costs ~ 240 USD/kg. Coal is dirt cheap: only 6.5 cents per kg in the US. Oil ~ 10x coal.
- Equipment for collecting, distributing, & storing *dilute* sources of renewable energy will always be more expensive than that which burns coal (stationary) or oil (transportation) until they run out.
- Nuclear energy in 1 kg *uranium* or *thorium* is *2.3 million times* that contained chemically in 1 kg coal. Not to be dismissed out of hand.

3,218 turbines, 615 MWe peak

2 reactors, 2,200 MWe peak

San Gorgonio vs. San Onofre

# 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

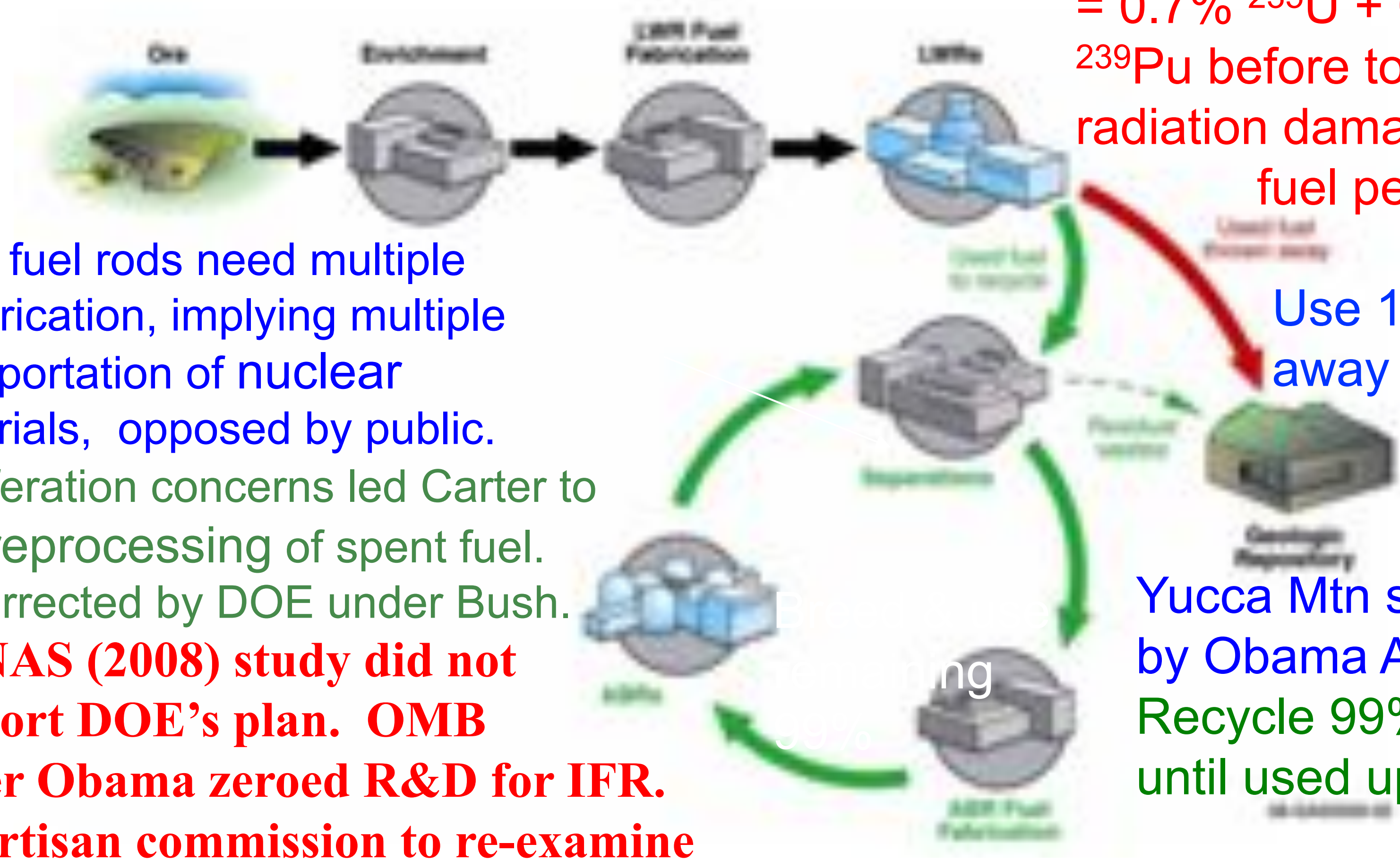
# Tale of Two Cycles

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

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

- Fermi’s objection to thorium cycle: Pa-233 with half-life of 27 days, has a fairly large probability for additional n capture. Wastes n in creating U-234, and breeding ratio drops below 1.
- With slow neutrons, Pu-239 has same problem -- captures n to become Pu-240, etc., often enough relative to fisssioning as to require n’s not to be slowed down for Pu-239 breeding – liquid sodium fast breeder.
- Wigner’s answer: build a *liquid-based* reactor, and chemically extract Pa-233 on a short time scale (e.g., every week) before it has a chance to capture a n.
- 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. Huge mistake not to have explored both paths.

# 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.

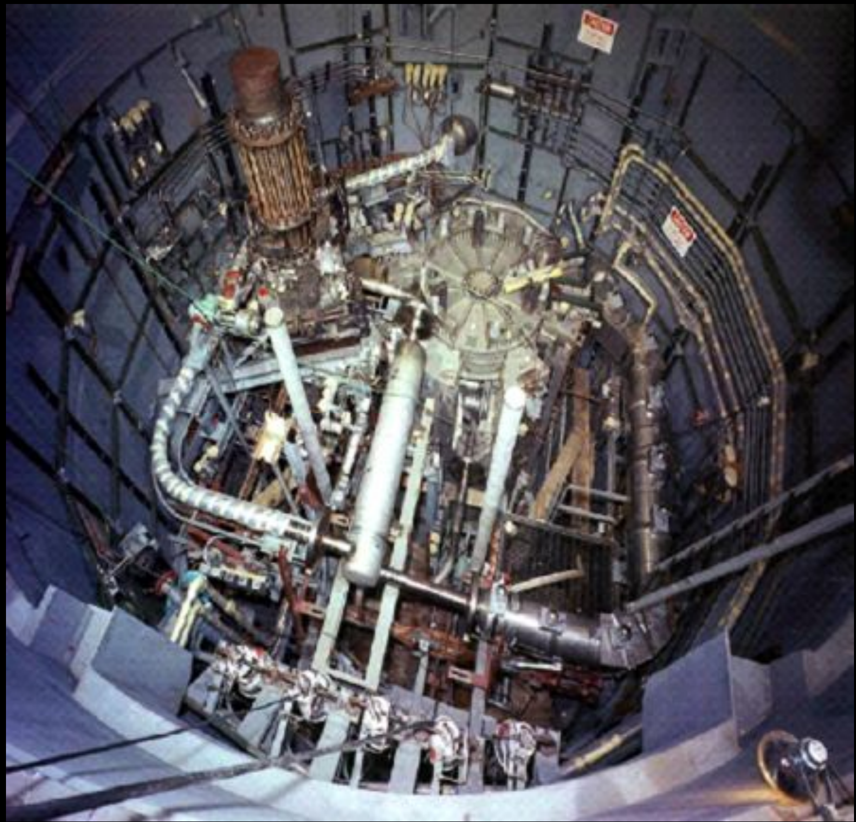
Proliferation concerns led Carter to ban reprocessing of spent fuel. Resurrected by DOE under Bush.

**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.

# Transformative Technology
# I. MSRE

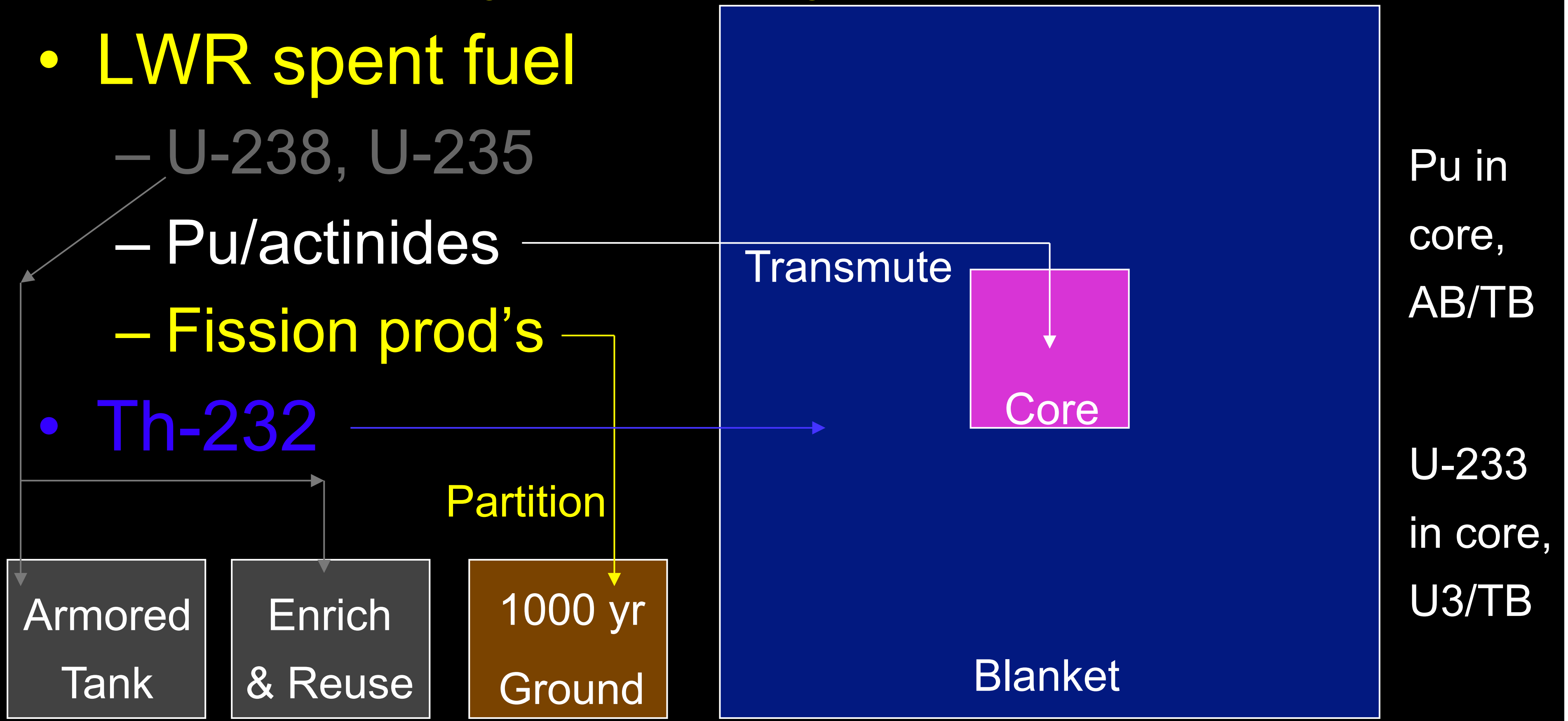


- Built by ORNL in 1960s, originally in response to US Air Force desire for nuclear powered airplane (cancelled)
- Never applied to civilian power generation:
  - Destroys Pu (does not make it)
  - No fuel fabrication needed
  - No enrichment needed
  - Complete burnup if Th-232/U-233 is adopted fuel cycle
  - However, > 1 breeding never demonstrated:
    - Fission product (lanthanide) removal is difficult in single-fluid MSRs where Th-232 is co-mingled with U-233
    - Reactors built of metal have too much n absorption

# 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-238, U-235
  - Pu/actinides
  - Fission prod's
- Th-232




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

# Carbon-Based Materials


- Graphite used since dawn of nuclear age to slow down n.
- Not corroded by molten salt.
- C/C composite = engineered graphite: graphite matrix (from coal tar pitch) + C fiber fabric. Can withstand high *T.* Strength greater than steel, but vulnerable to sharp blows
- Carbon vapor or graphene deposition to make graphite impervious to liquids/Xe-135.
- High thermal conductivity (or low -- insulator -- depending on fiber orientation). Nearly zero CTE (leak resistant).
- Awarded NSC grant to develop 5 MWt C-based HX.

# Two-Fluid MSR

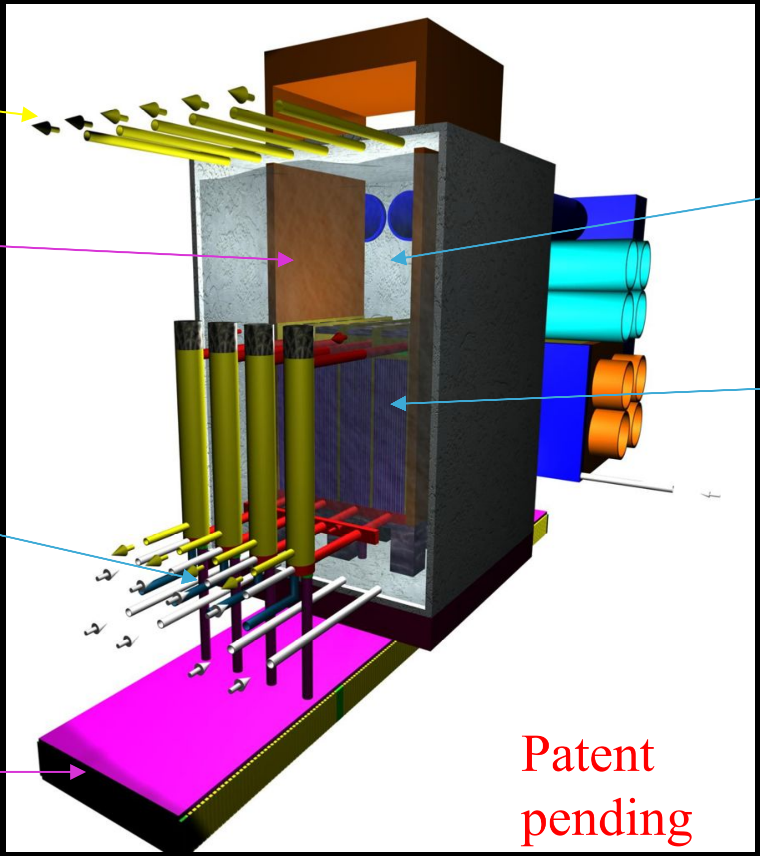
Except for dump tank, system built from C-based materials

He purge of gaseous Xe-135

Active/passive control

Passive safety feature 4: 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 & 3: Lose coolant salt, lose n reflector; if over-heated, fuel salt expands out of reaction zone.

Breeding ratio for U3/TB can be as high as 1.12 without extracting Pa-233 (diluted in 100 $m^3$ pool; activate NaF).

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.

# Transformative Technology
## II. Artificial Coal & Syngas

High throughput pathway to making solid, liquid, and gaseous biofuels.

Patent pending

# Taipower Assay: Torrefied Chopsticks/Bamboo

| Quality | Biocoal |
|---|---|
| Useful heating value | 6013 kcal/kg (10 min at 300 C) |
| Hargrove Grindability Index | 59 |
| Sulfur content | 0.24% chopsticks with $SO_2$ treatment?<br>0.05% bamboo without $SO_2$ treatment |
| Ash content | 2.37% chopsticks - 2.87% bamboo<br>(45% KO equivalent fertilizer feedstock) |
| Moisture content | 4.91% |

C-neutral if replanting accompanies burning; C-negative with CCS; no waste

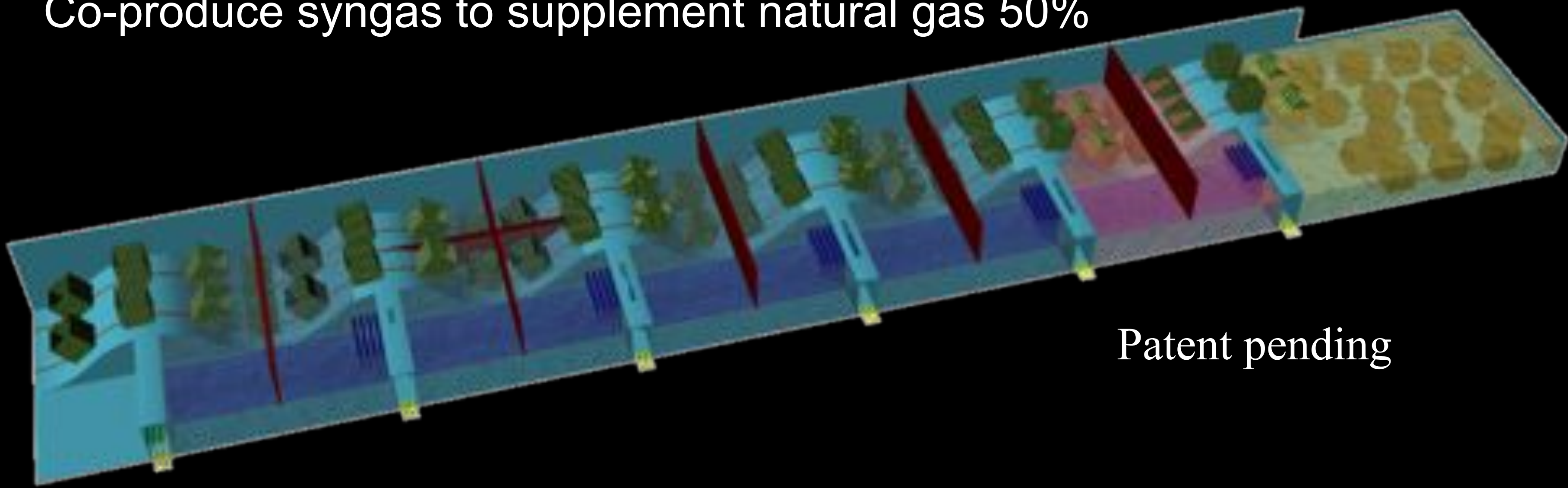
# MSR 320 MWt Input ➔ 76 tonnes biocoal/10 min

Can fuel 1.4 GWe coal-fired power plant (240 in US)

Each power plant needs biomass from 75 km x 75 km bamboo farm

Land area of State of Mississippi for all US coal-fired power plants

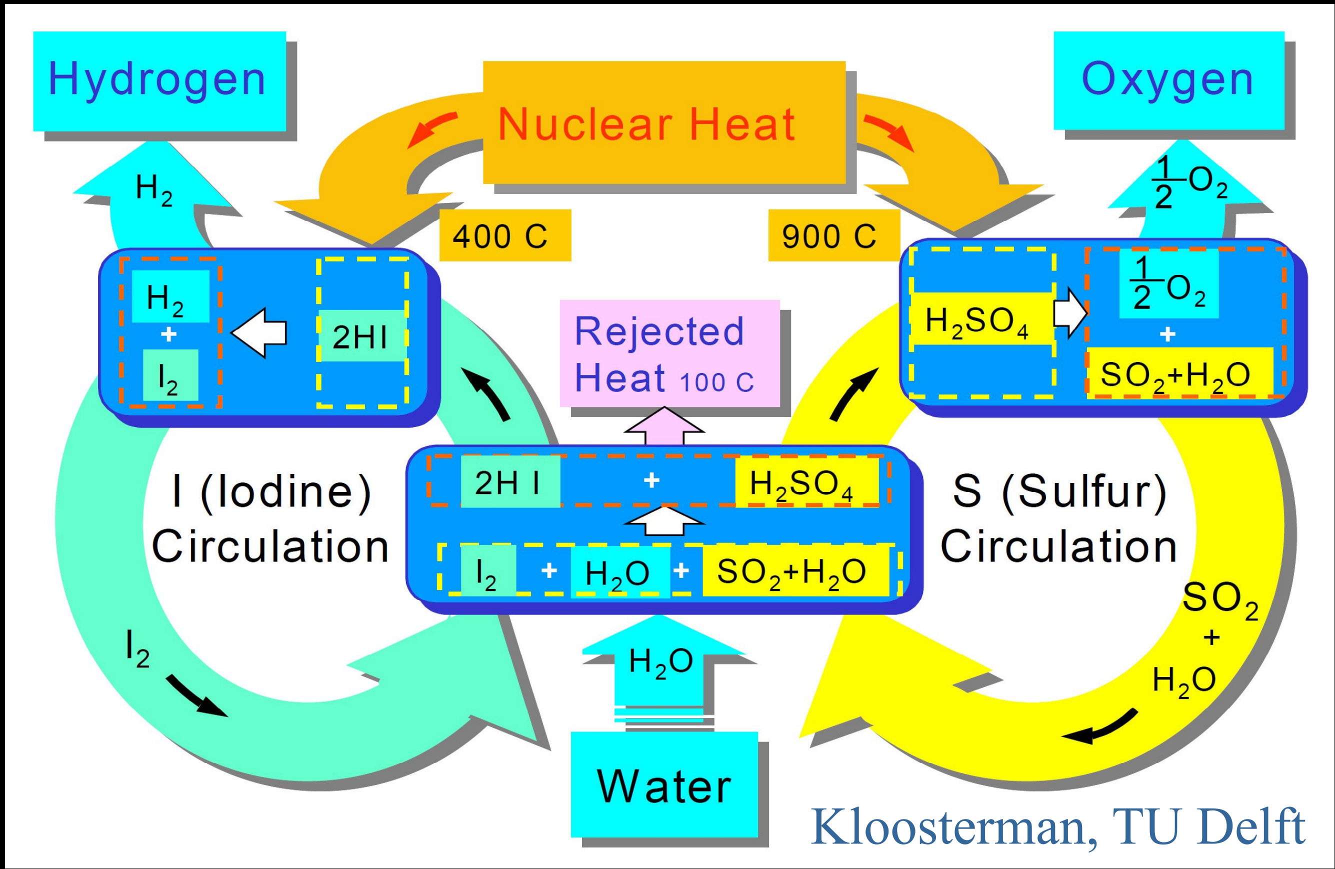
Co-produce syngas to supplement natural gas 50%



Patent pending

# Transformative Technology III. High-$T$ Dissociation of $H_2O$

For fuel cells or liquid biofuels




For carbon capture & sequestration

# We All Inhabit this Small Planet

- Saving the Earth is still possible (barely), but it requires environmentalists to stop fighting nukes (on thorium fuel cycle) as source of clean energy.
- John Fitzgerald Kennedy (June 1963):

2nd Youngest President of United States

Apollo Mission to Moon

December 1968

- "So, let us not be blind to our differences – but let us also direct attention to our common interests and to the means by which those differences can be resolved. And if we cannot end now our differences, at least we can help make the world safe for diversity. For, in the final analysis, our most basic common link is that we all inhabit this small planet. We all breathe the same air. We all cherish our children's future. And we are all mortal."
- So, let us set aside our differences. Let us rally our spirits in a season of financial adversity. Let us unite in a common cause to save the world.

Climate Change and Energy Solutions
Frank H. Shu
UCSD, Academia Sinica, U Michigan
24 January 2011
Collaborators: M. J. Cai, F. T. Luo, HX Team
Frank H. Shu


Nuclear Energy: Reprocessing & Breeding
Proliferation concerns led Carter to ban reprocessing of spent fuel. Resurrected by DOE under Bush.
Use 1% throw away 99%.
Yucca Mtn stopped by Obama Adm
Recycle 99% until used up.