Nuclear Energy After Fukushima

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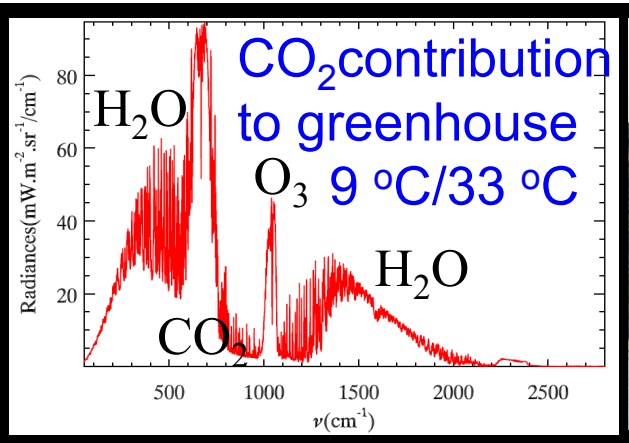
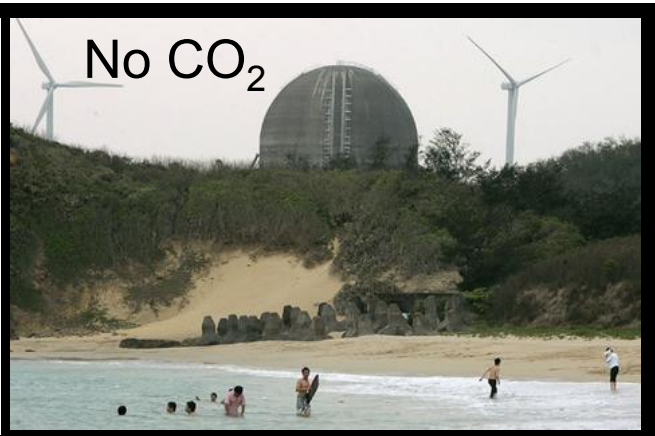




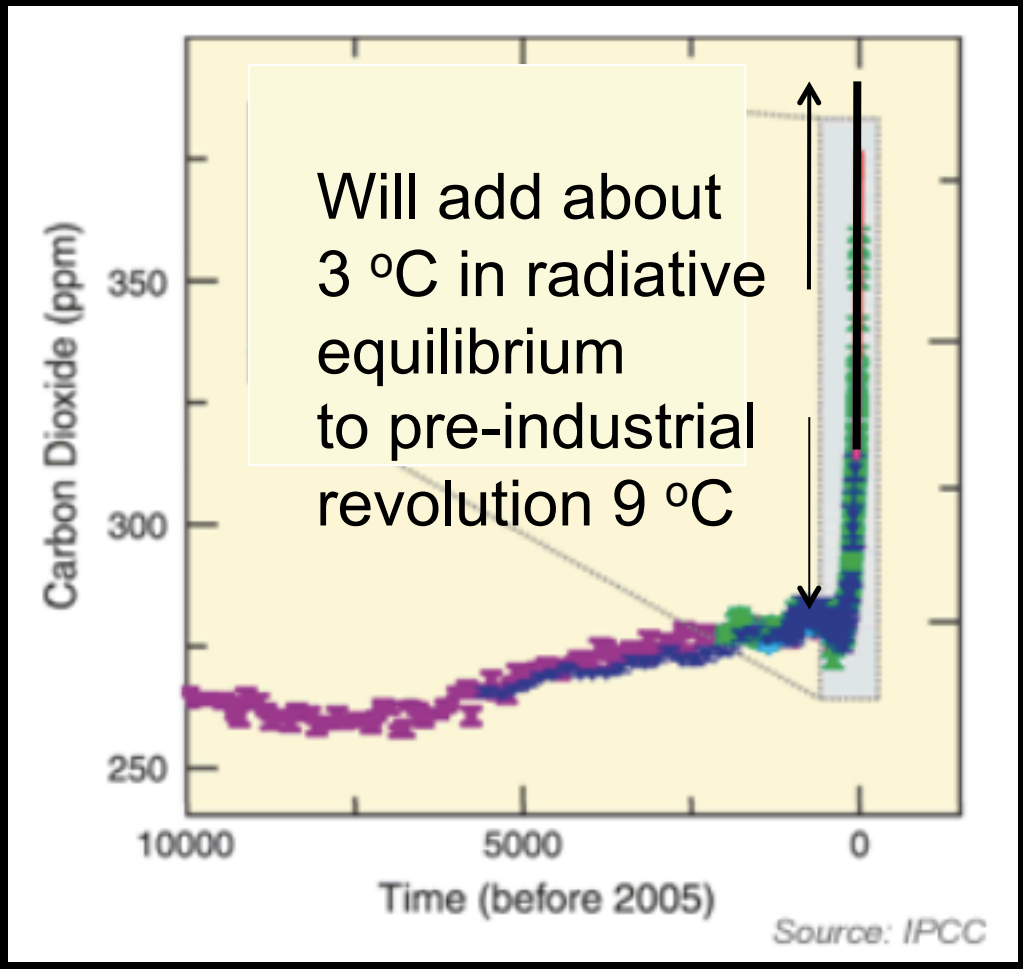
Outline of Talk

- Fossil Fuels and Climate Change
- Limitations of Renewable Energy Sources
- Nuclear Power after Fukushima
  - Safety of different nuclear fuel cycles
  - Advantages of molten salt reactors
    - Application to biofuel production
    - Application to thermal-chemical dissociation of H_2O
- Summary

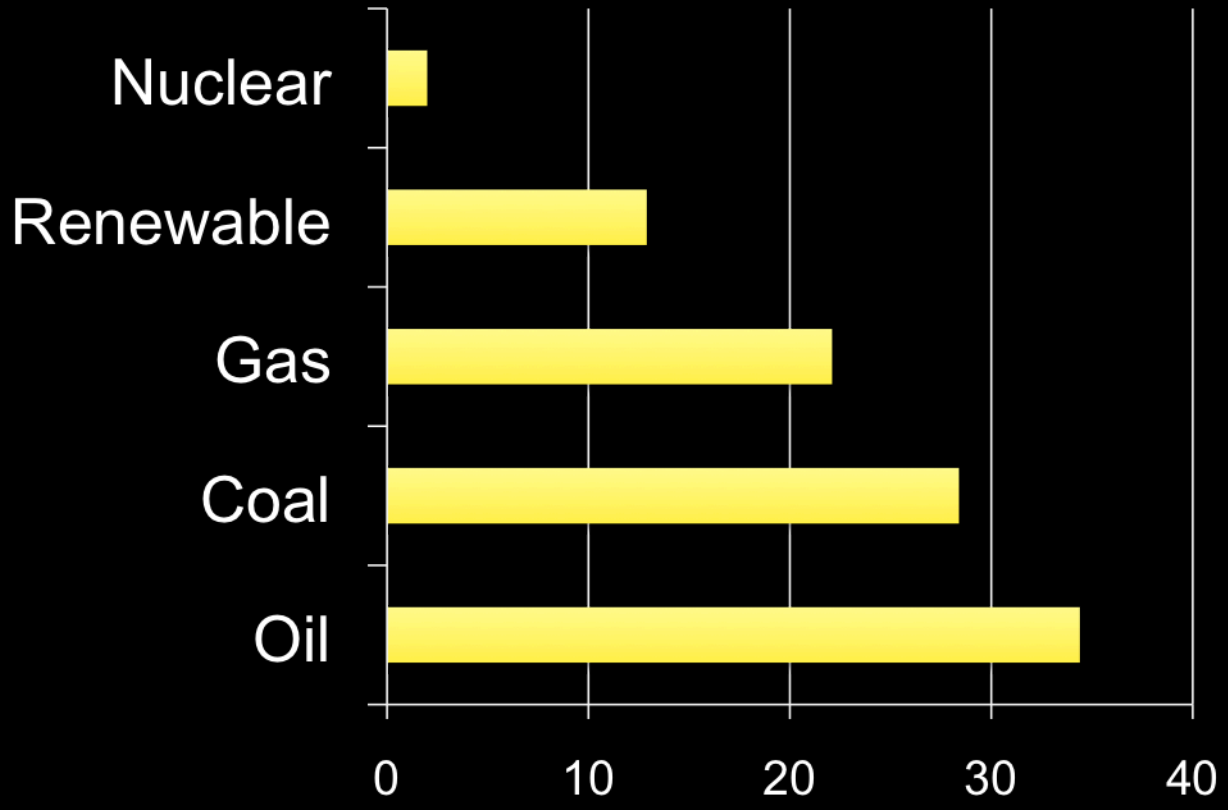
Grand Challenge of 21st Century

"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.



Share of World Energy Generation in 2008 (IPCC)



Nuclear: 6% if thermal

Renewable: 12.9% tot
- Wood: 6.3%
- Biofuel: 4.2%
- Hydro: 2.3%
- Wind: 0.2%e→0.5%t
- Geothermal: 0.1%
- Direct solar: 0.1%

Myth: Nuclear is displacing renewable. Reality: Despite heroic levels of investments, renewables are *not* displacing fossil fuels 38 yr after 1st oil crisis.

Fossil vs. Renewables vs. Nuclear

- Coal is a very *concentrated* form of chemical energy – 40 x Li ion battery per kg. Latter can be recharged ~ 1000 times, but costs ~ 8000 NTD/ kg. Coal is dirt cheap: only 3 NTD/kg. Coal ~ 0.1 battery. Oil ~ 10 x 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).
- Nuclear energy in 1 kg *uranium* or *thorium* is *2.3 million times* that contained chemically in 1 kg coal.

1830 turbines x 5 MWe = 9.15 GWe, on only 30% of time. 4th Nuc: 2.7 GWe on 90%. Likely cost: 1 TNTD = 3 x 4th Nuc with 1/3 of life

Taiwan's Choices

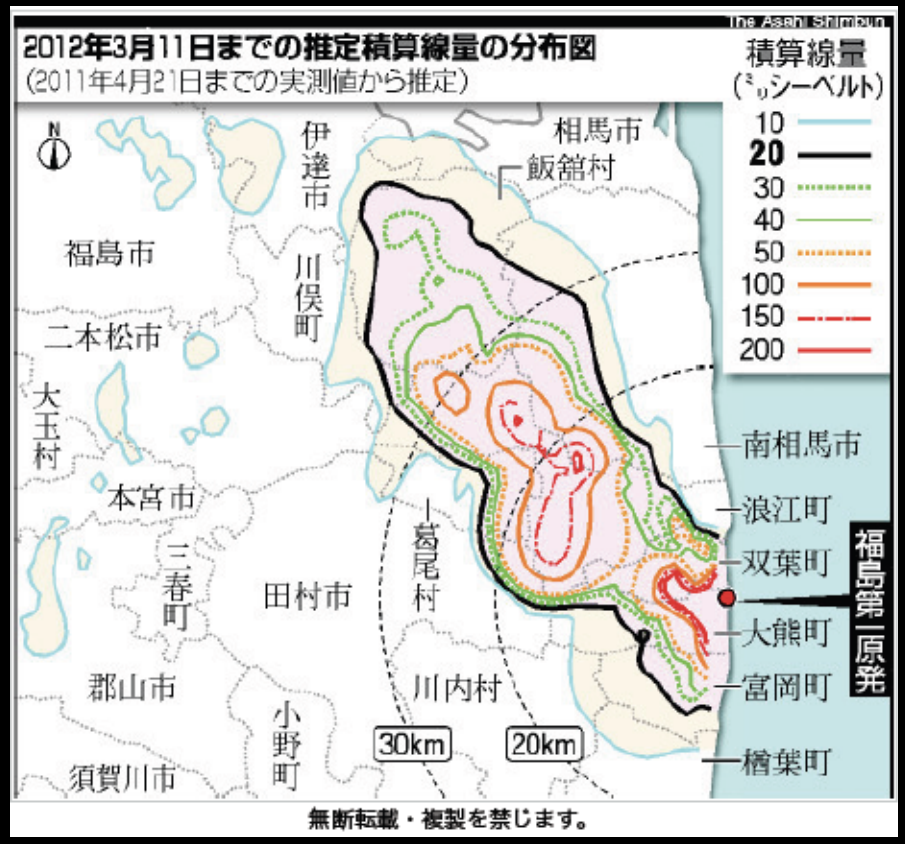
- Present capacity 167 GW
- Hydro: 0.2 GWe avg
- Wind: max 3 GWe (avg)
- Solar PV: 6 x coal = 50% GDP, 100% if want electricity at night
- RE's lack of market penetration because of intrinsic limitations
- Realistic choices: nuclear or fossil fuel (coal/oil/gas) or do w/o
- "If you're anti-nuclear and anti-CO_2, then you're pro-blackouts"

Major Earthquakes since Nuclear Power in Taiwan

Locale	Yr/Mag	Deaths	Property	Nuclear	Deaths	Property
Mexico	1985/8.1	10,000	4 GUSD	Yes	None	None
Armenia	1988/6.9	25,000	4 GUSD	Yes	None	None
USA, SF	1989/7.0	68	6 GUSD	Yes	None	None
JP, Kobe	1995/7.2	6,434	100 GUSD	Yes	None	None
Turkey	1999/7.6	17,127	20 GUSD	Not yet	None	None
TW,Nantou	1999/7.3	2,418	14 GUSD	Yes	None	None
In Ocean	2004/9.2	230,000	Unknown	Yes	None	None
CN,Szech	2008/8.0	68,000	86 GUSD	Yes	None	None
Chile	2011/8.8	486	25 GUSD	Not yet	None	None
JP, Tohuku	2011/9.0	27,000*	300 GUSD	Yes	None?	30 GUSD

*Tsunami warning system; buddy system in schools; accelerometers on high-speed rail; elevators sent to ground fl; shutoff natural gas; make reactors safer

Fukushima: Long-Term Legacy



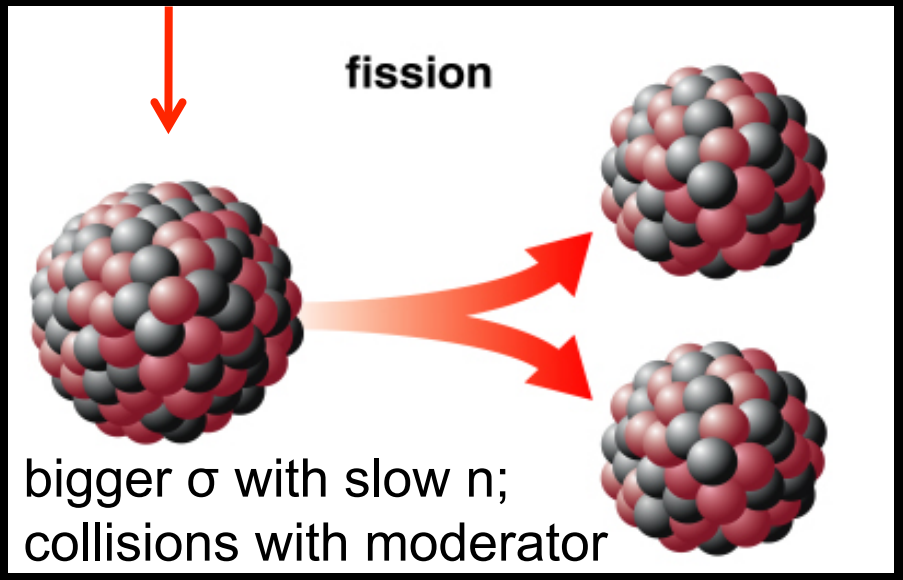
20 mSv/yr = 13 x average Taiwan
= 1/5 x Ramsar Iran (radon)

- Low-level radiation (I-131 $t_{1/2}$ = 8 d; Cs-137 & Sr-90 = 30 yr) lasting decades w/o decontamination
- To continue using nukes, make reactors safer, and eliminate human factors as much as possible
- In case of accident, must contain I-131, Cs-137, Sr-90.

Chain Reaction, Breeding, Radioactivity

Fissile (odd number n):
U-235 (0.7% of U-238)
U-233 from Th-232 + n
Pu-239 from U-238 + n

n +



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

+ 2 or 3 n

> 1 chain reaction

> 2 breed

Subcrit wrt prompt n
Supercrit wrt delayed n

Problem: radioactivity & decay heat of fission products with $t_{1/2} \leq 30$ yr

Fuel Cycles

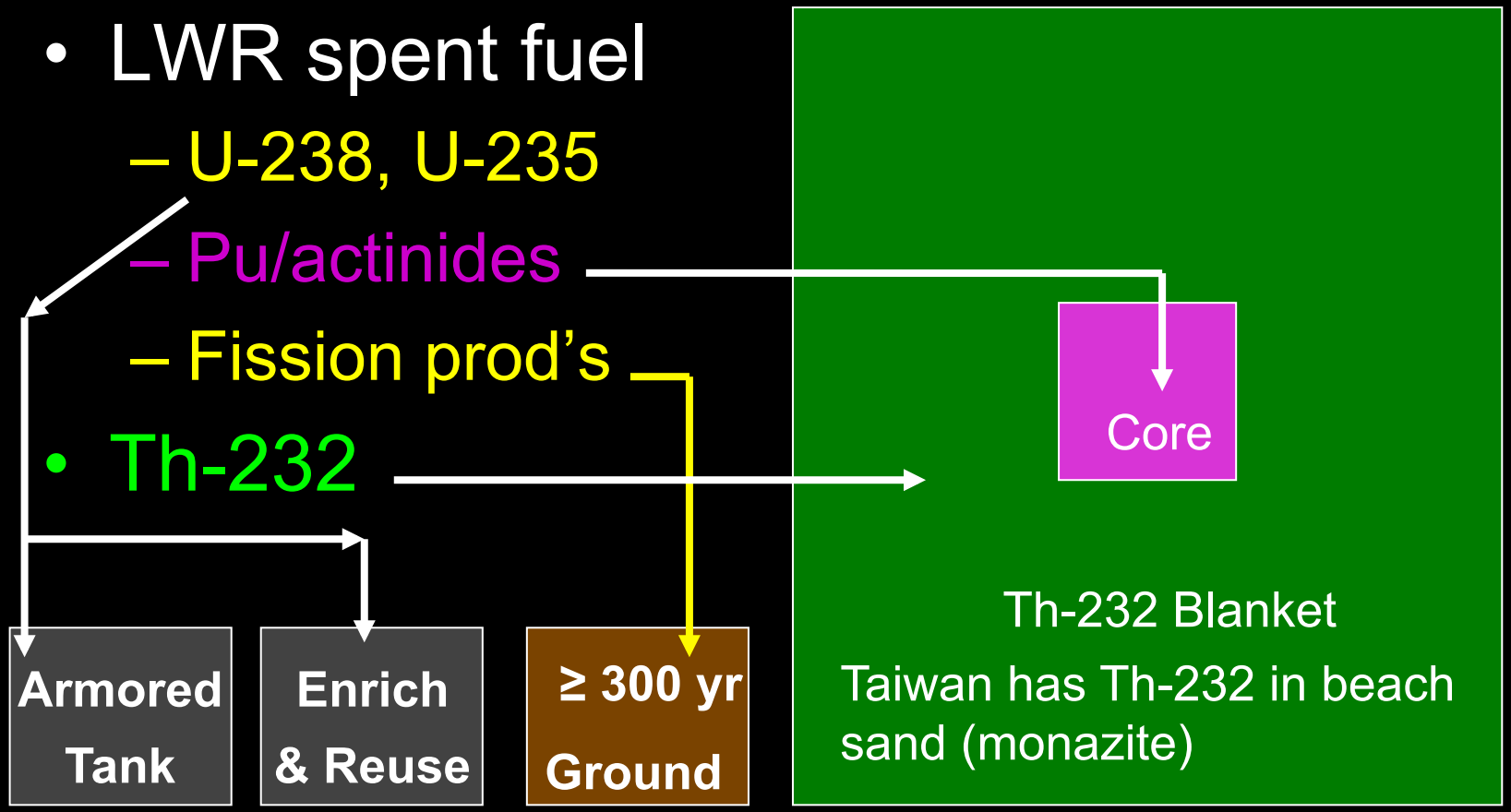
Nuclear fuel	U-235	Pu-239	U-233
Fuel form	Solid pellets	Solid pellets	Molten salt
Burn-up	1% (net, stopped by rad damage)	100% possible by refabrication	100% possible by circulation
Waste storage	240,000 yr	300 yr, burn Pu-239	300 yr, only FP
High-grade ore	6 yr if supply all	600 yr	2,000 yr
Moderator	Water, slow n w absorption	None, fast n to breed	Graphite, slow n w/o absorption
Coolant (usual)	Water	Liquid sodium	Fluoride salt
Number built	500 (civilian, built > 30 yr ago)	15 (US, USSR, UK, Ger, Japan, India)	2 (ORNL, but made of metal)

Chernobyl: graphite moderator, water coolant, only nuclear accident with runaway chain-reaction

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

Chain reaction, breeding, & processing in liquid $NaF\text{-}BeF_2$

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



Pu in core turns Th-232 into U-233

U-233 in core gives breeder

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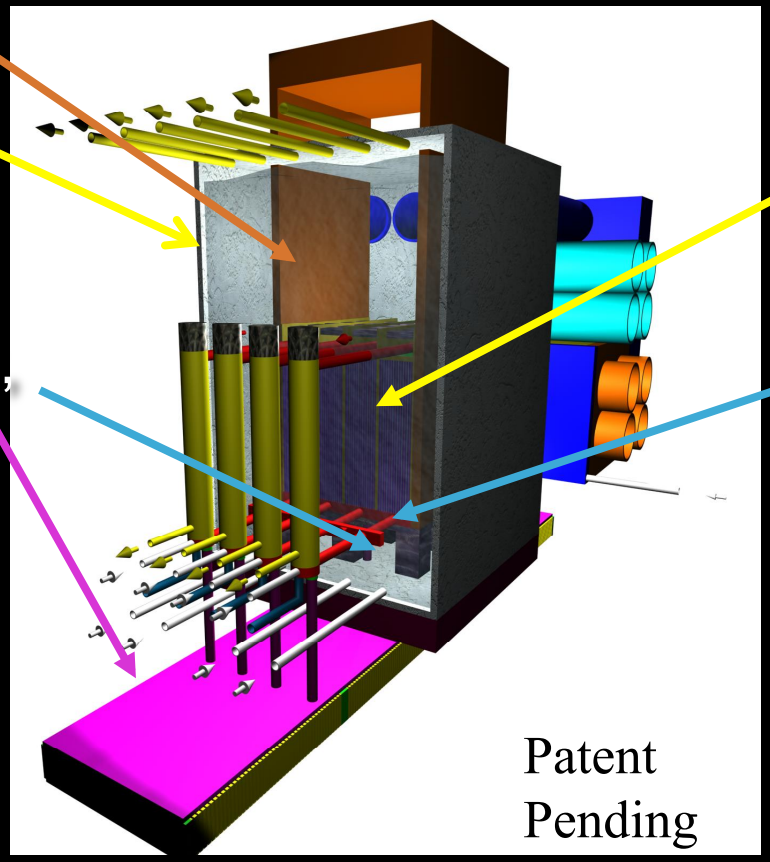
Two-Fluid Molten Salt Reactor

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

Active/passive control

2 containment walls.

If *T* still rises, frozen plug melts; fuel salt drains into dump tank, which is air-cooled to remove decay heat (cannot lose air). Salt inert, low vapor *P*: no fire, no explosions. Fuel not solid: no radiation damage, no meltdown, no TMI.



If over-heated, fuel salt expands out of reaction zone. Online distillation of fission products. Circulate until 100% burn-up. Spill: NaI, CsF, SrF_2 in salt that freezes in 10 s.

Thick steel dome, no Chernobyl, no Fukushima, no jet crashes. Burn Pu, U-232 accompanies U-233, no bombs.

Use MSR Heat to Make Biofuel

High-throughput production of artificial coal, liquid biofuel, & syngas for coal-fired power plants, heavy transportation, & natural gas, preserving existing infrastructure (leverage each 1 watt nuclear power ➔ 7 watt biofuel)

Patent Pending

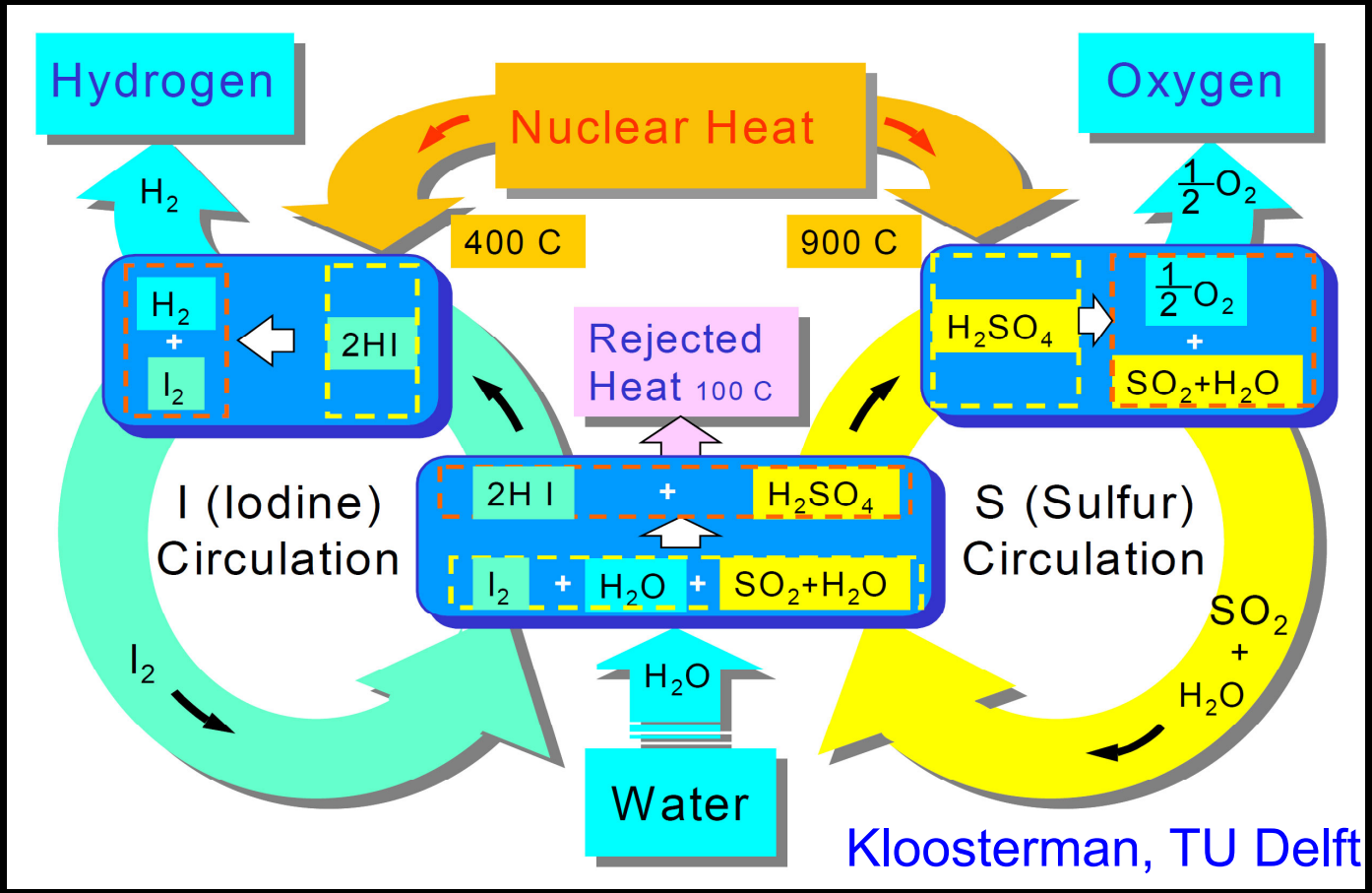
Taipower Assay: Supertorrefied Bamboo

Quality	Biocoal
Useful heating value	6139 kcal/kg (10 min at 300 C)
Hargrove Grindability Index	67
Sulfur content	0.06%
Ash content	5.69% (mostly potash = fertilizer)
Moisture content	8.65% (depends on drying method)

Partner CSBC & Taipower for equipment & commercial scale-up

Use MSR Heat to Make Water into a Fuel

For H fuel cells or liquid biofuel



For carbon capture and seques-tration

Summary

- Saving the Earth is still possible, but it requires physicists to speak up & environmentalists to stop opposing nuclear power, the only C-free alternative that can replace fossil f's.
- The public is correct to insist on safe, affordable nuclear power with low proliferation risk and waste.
- Not developing MSRs (the road not taken forty years ago) in parallel with LWRs was a big mistake.
- Nuclear power plants must be evaluated on a realistic cost/benefit basis. The risks are occasional accidents, but massive releases of radioactivity are preventable. The benefits are a much lower environmental footprint, energy security, and sustainable development for the millennium.