Two challenges that must be dealt with if nuclear power is to contribute in a more significant way as a climate-friendly source of energy:

Safety and Proliferation Resistance

Frank von Hippel, Program on Science and Global Security, Princeton (a piece of Princeton’s original Center for Energy and Environmental Studies)
Symposium on “Destiny Studies for a Small Planet”
in honor of Robert Socolow’s retirement
Maeder Hall, Princeton University, 15 April 2019
SAFETY: Chernobyl (1986) was a Soviet & European trauma. >100,000 relocated from ~5,000 km², high doses to 600,000 liquidators, a regional thyroid-cancer epidemic plus an estimated 10,000-50,000 additional cancer deaths in Europe

Designers knew they could be unstable but did not tell the operators. No regulators.

17 reactors of this type built.
Rapid growth of nuclear capacity ended globally. Nuclear *share* has declined from ~17% to 10% in two decades.
Fukushima (2011): Not as bad as Chernobyl but costly

165,000 relocated (~1/2 voluntary)
~$200 B est. cleanup & compensation
~$100 B extra for LNG,
~ $30 B in nuclear-safety upgrades
~$300 billion total, greater than cost of Japan’s power reactors
~ 1000 cancer deaths estimated

TEPCO, Japan’s largest utility,
slow-walked upgraded tsunami prot.,
filtered vents in case of containment overpressure rejected, now required in Europe and Japan but still not in US.

Tsunami
15,000 deaths,
500,000 made homeless
100x worse accident almost happened at Fukushima (in fact was believed to be happening)
Averted by good luck: Water leaked into the pool from adjacent reactor well, which was supposed to have been emptied.
Chairman of Japan’s AEC told Prime Minister “it might be necessary to evacuate Tokyo”

Actual Fukushima accident
88,000 relocated (1,100 km²)

Hypothetical fires in spent fuel pool #4

Wind toward ocean
800,000 from 2,600 km²

Wind toward Tokyo
29,000,000 from 25,000 km²

Actual Cs-137 contamination
190 km

Red or orange: Compulsory Relocation

MBq/m²

>0.5

>1.5

>4.5

8 April 2011

Fukushima Daiichi

Hypothetical spent-fuel fire, 9 April 2011

Hypothetical spent-fuel fire, 19 March 2011
Spent fuel fire in a dense-packed pool at NRC’s average nuclear power plant, Surry in Virginia

1 Feb. 2015

1 April 2015

1 Sept. 2015

Red or orange: compulsory relocation. Consequences outside circles not include in NRC cost-benefit calculation.

8 million *average* relocated
$2 trillion *average* economic cost
(NRC consequence calc. w. 3 errors corrected)
NRC estimated release/100 if fuel transferred to dry casks after 5-year pool cooling.
Not required because of low probability est.
New construction vs. retirements
Loss of trust + increased costs (except China?)
New types of reactors?

- Many reactor types on which R&D was conducted in 1960s but which had major problems and were not able to compete economically with water-cooled reactors being promoted (liquid sodium-cooled, molten salt…).

- Small-modular water-cooled reactors promoted but economies of scale in production probably not large enough to compete with large nuclear power reactors.

- If large water-cooled reactors cannot make it in the market, it is not clear that any other reactor type can.
Bottom line (nuclear safety)

An unforgiving technology and unforgiving public.

A much worse accident almost happened at Fukushima.

Those who want a nuclear-energy renaissance should not be pushing for neutered safety regulation.
PROLIFERATION

Uranium provides two paths to nuclear power and the bomb

Separate (enrich)
0.7% chain-reacting

U-235

Convert U-238 into Pu-239 by neutron absorption in a reactor core and separate from the fission products
Original Acheson-Lilienthal (J. Robert Oppenheimer) Non-proliferation Proposal (1946)

Put “dangerous” nuclear activities under international control:
• Uranium enrichment
• Plutonium separation

Proposal was first casualty of the Cold War.
Spread of nuclear weapons & power. Now problem again in Middle East.

Under construction: Bangladesh, Belarus, Turkey, UAE, Saudi Arabia.
Planned. Egypt

US allies, western hemisphere, former USSR

+ Iran, S. Africa

Weapon states

Power states

Atoms for Peace

Nonproliferation Treaty

South Africa, (Pakistan) with enrichment

DPRK

Spread of nuclear weapons & power. Now problem again in Middle East.
PLUTONIUM SEPARATION

US AEC 1960s vision of a “plutonium economy”

Chain-reacting U-235 only 0.7% of uranium.

*Liquid-sodium-cooled fast-neutron breeder reactors could make more chain-reacting plutonium than they consumed, making U-238 their fuel.*

Breeder reactor would turn earth’s crust to super-coal!

Fission of 3 grams of U-238 in an average ton of rock equivalent to combustion of 9 tons of coal.

*~ 1 ton of U-238 (plutonium) per GWe-year*

*also enough for 100-300 nuclear bombs.*

Fortunately, invisible hand did not favor the plutonium economy.

Sodium-cooled reactors more costly, less reliable than water-cooled.
Plenty of low-cost uranium, only ~0.3 cents /kWh today
Only 2 breeder prototypes today (in Russia)
+ 1 each under construction in India & China
But separation of civilian plutonium continues!  
(– originally for startup fuel for breeders)
5 countries still committed to reprocessing: 4 nuclear-weapon states + Japan

- UK finally stopping, no plans for use or disposal yet
- Russia for future breeders
- Japan, for recycle in LWRs
- France, for recycle in LWRs
- Belgium, Germany, Netherlands, Switzerland
- China (0.04)
- India (~6 tons)
France and Japan abandoned their breeder programs but decided to recycle plutonium in light-water reactors. Costs 5-10 times as much as the 15% of LEU fuel it replaces.

France drives truck loads of plutonium from north to south. Greenpeace has intercepted at gas station.
Uranium Enrichment

• Uranium enriched <20% not directly weapon useable

• All nuclear power plants today (except for some breeder reactors) use fuel enriched to less than 5%.

• However, a modern enrichment plant can quickly be reconfigured to produce weapon-grade uranium (> 90% enriched).

• Issue therefore is spread of uranium enrichment capacity.
Large enrichment plants owned by Russia, URENCO, France, China, Argentina, Brazil, Iran, Japan have small, uneconomic plants fuel for nuclear-submarine program (Brazil) + nuclear-weapon option. URENCO is multinational (Germany, Netherlands, UK) a better model.
A virtual nuclear arms race in the Middle East? Saudi Arabia wants same right to enrich as Iran. Turkey, Egypt next? *Multinational enrichment would be better.*
**Bottom line: Modernize Acheson-Lilienthal**  
(International $\rightarrow$ multinational control,  
better than proliferation of national facilities)

**Plutonium separation and breeders uneconomic for foreseeable future:**
- Limit to multinational R&D at one or two sites like ITER  
  (International Thermonuclear Experimental Reactor in France)

**Enrichment:**
- Limit nuclear fuel enrichment to less than 20%, including for naval propulsion reactors (China, France already fuel their submarines w. LEU.)
- Phase out national enrichment in favor of a few multinational suppliers.