Nuclear Energy Present and Future

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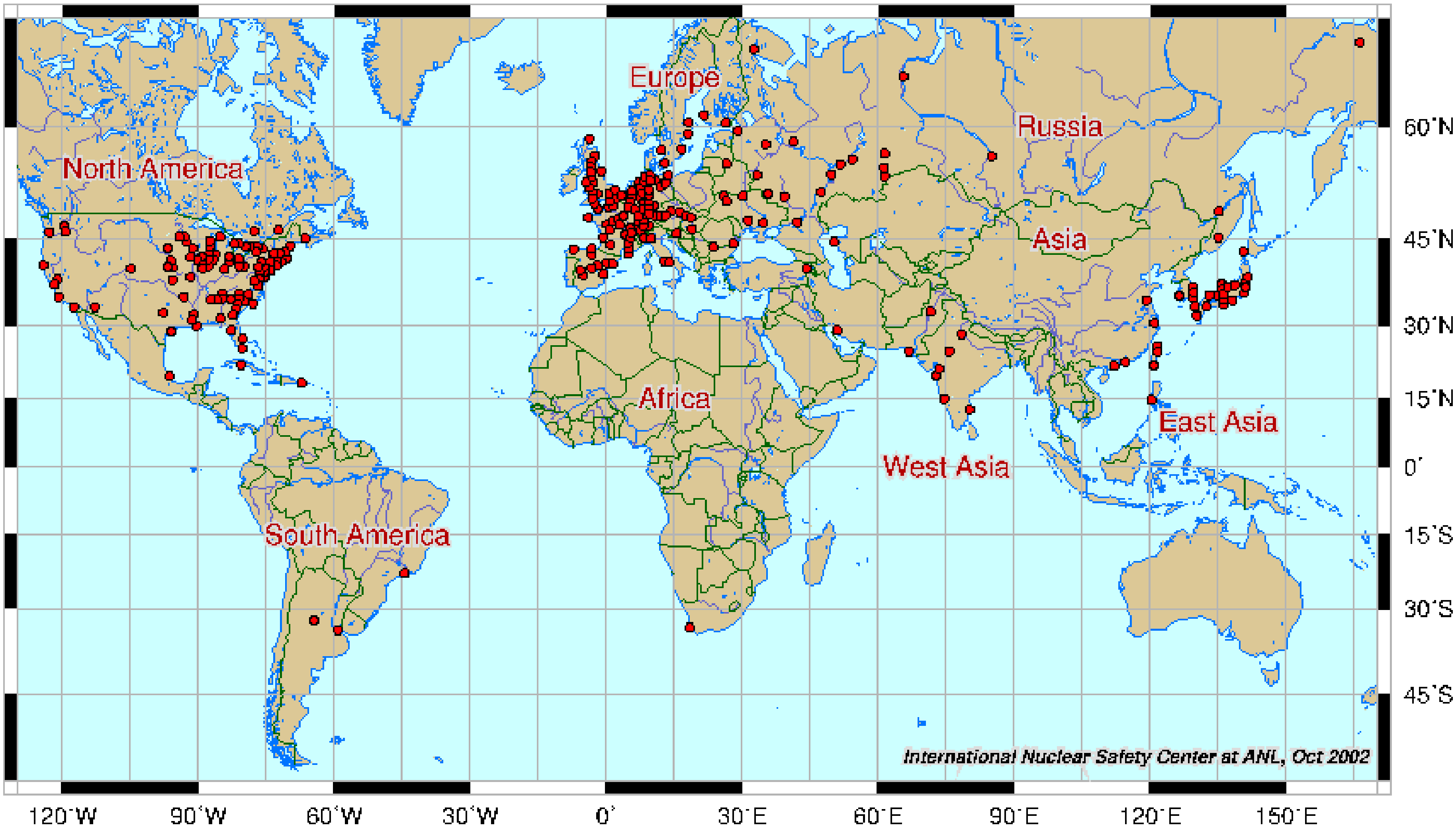
Outline:

- Nuclear Power in the US and the World
- Limitations and Challenges
- Research and Technical Opportunities

Nuclear Power Plants Worldwide

- US: 103 plants in operation, none under construction
- World: 442 plants in operation, 28 under construction



380 GW, 3.7% increase in 2004, 16% of world electricity.

New Plants are coming on line

Nuclear Power Plant Status changes: 2005/6 highlights (IAEA)

New units entering operation: 6 reactors, +6.5GW

- Khmelnitski 2 (950 MW(e), PWR-WWER, Ukraine) operation 7 Sep 05
- Shika 2 (1304 MW(e), ABWR, Japan) connected 4 Jul 05, ops 15 Mar
- Tarapur 4,3 (2x490 MW(e), PHWR, India) connected 4 Jun 05, 15 Jun 06
- Hamaoka 5 (1325 MW(e), ABWR, Japan) operation 18 Jan 05
- Ulchin 6 (960 MW(e), PWR, South Korea) connected 7 Jan 05
- Tianwan 1 (1000 MW(e), PWR-WWER, China) connected 12 May 06

Restarts after a long term shutdown:

- Pickering 1 (515 MW(e), PHWR, Canada) reconnected 26 Sep 05

Final shutdowns: 3 reactors, Sweden, Germany, Spain -1GW

Construction initiation:

- Olkiluoto 3 (1600 MW(e), EPR, Finland) - construction started 12 Aug 05
- Chasnupp 2 (300 MW(e), PWR, Pakistan) - groundbreaking 8 April 05
- Shin Kori 1 (960 MW(e), PWR, S. Korea) - construction started 15 Aug 06
- Lingao 4 (1000 MW(e), PWR, China) - construction started 15 Jun 06
- Qinshan II-3 (610 MW(e), PWR, China) - construction started 28 Mar 06
- Shin Wolsong 1&2 (960 MW(e), PWR, S. Korea) ground breaking 28 Apr 06

China: 2nd largest energy consumer

2004

Electricity growth

9% generation

16% demand

so still...

30GW shortage

Nuclear Expansion plan: 40GW by 2020. 2 to 3 new plants per year.

Some built by international companies; some to be domestic.

Electricity Generation in the US

20% of US Electricity is Nuclear

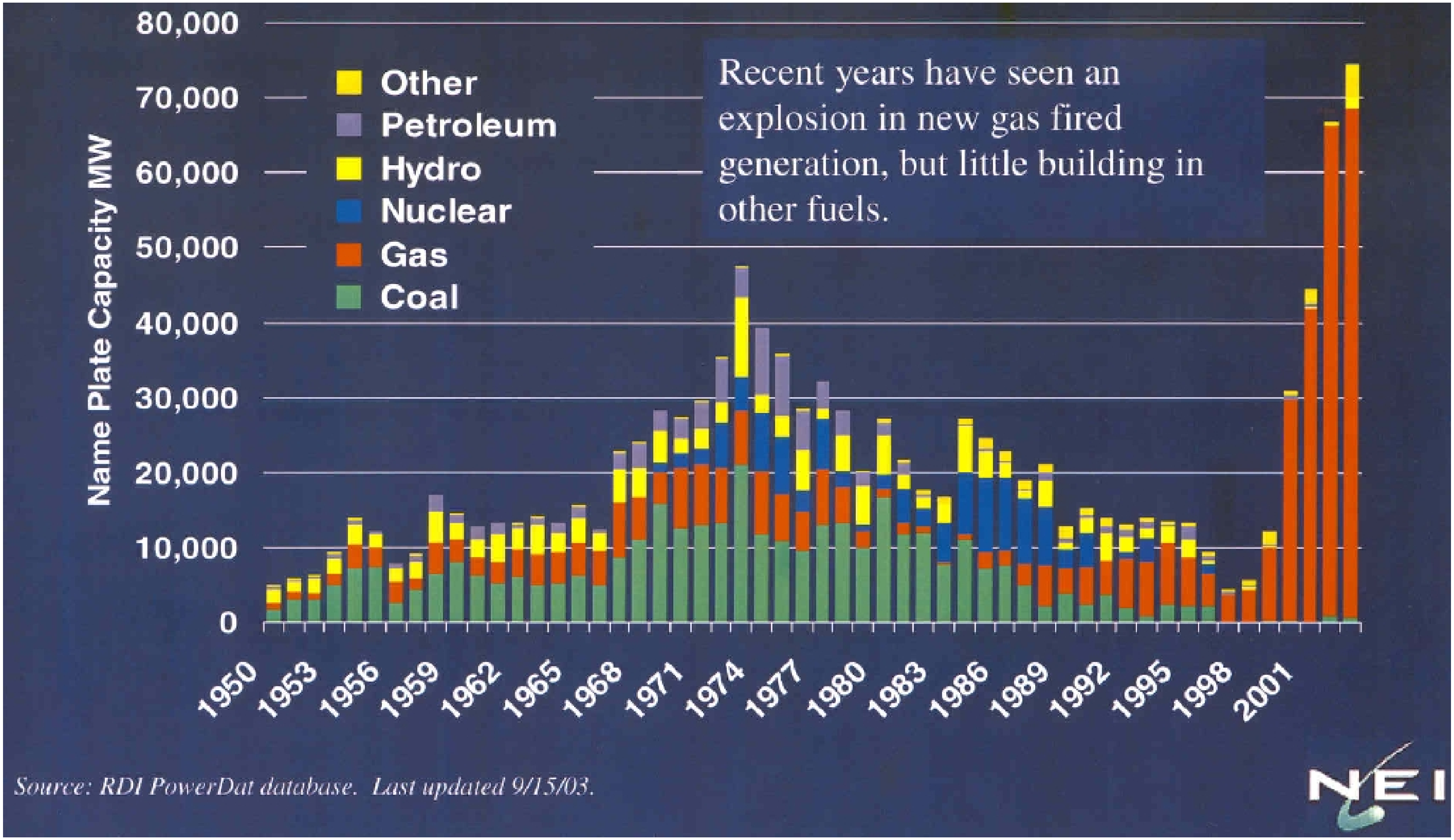
Electricity Source (2004) United States	% of total	¢/kWh	%Fuel
Coal	50.0	1.90	76
Nuclear	19.9	1.68	25
Natural Gas	17.7	5.87	91
Hydroelectricity	6.6		
Petroleum	3.0	5.39	88
Non-hydro Renewables	2.4		
Other sources	0.4		

Existing nuclear plant generation costs are the cheapest besides Hydro.

This is the opposite of what a 2003 survey found was the public's opinion. (They thought nuclear was the most expensive.)

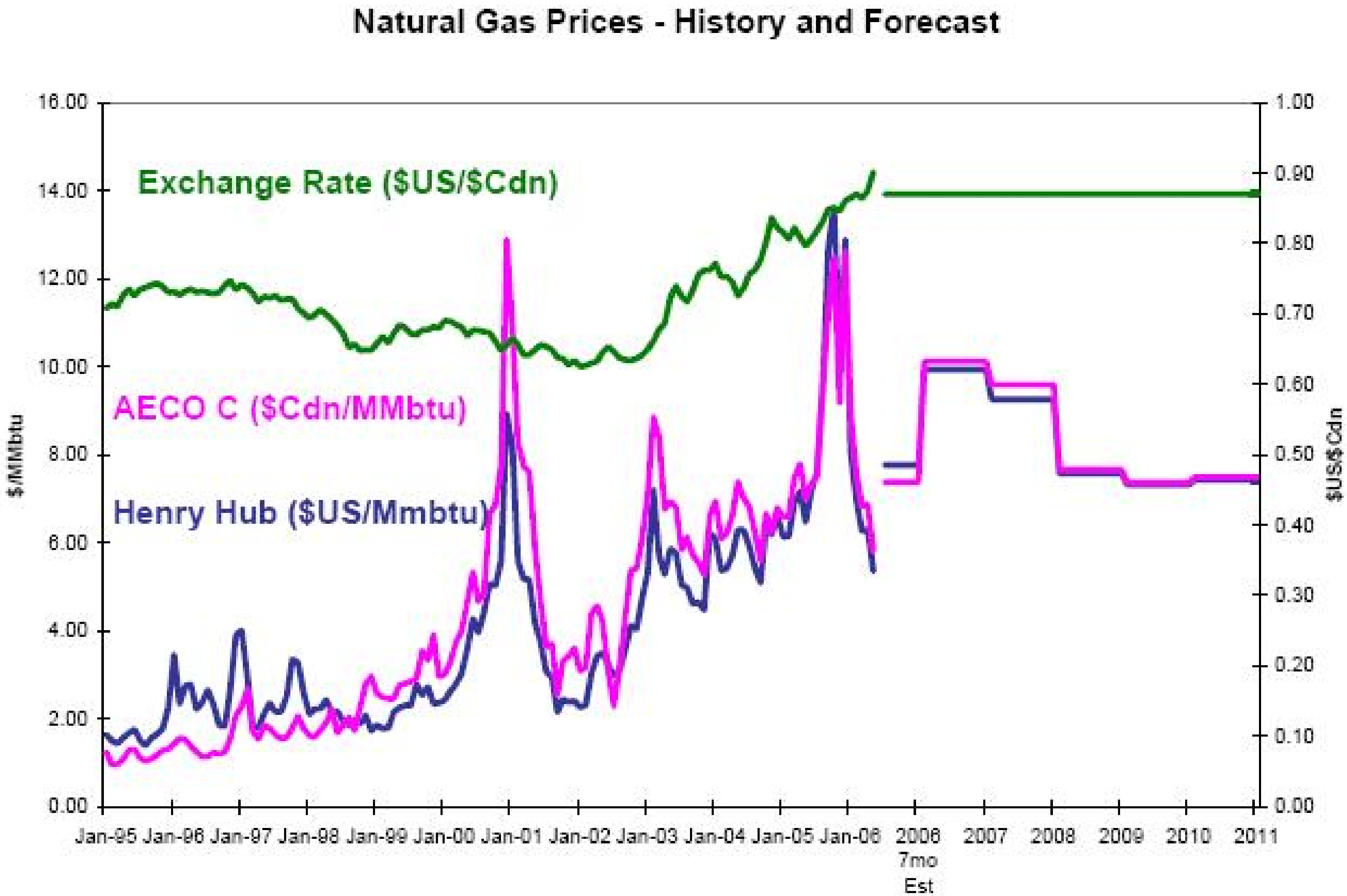
Opportunities to expand (inland) Hydro are few in US (and worldwide).

Gas Dominates recent past construction



These gas plants were ordered before the major price increases.

Natural Gas



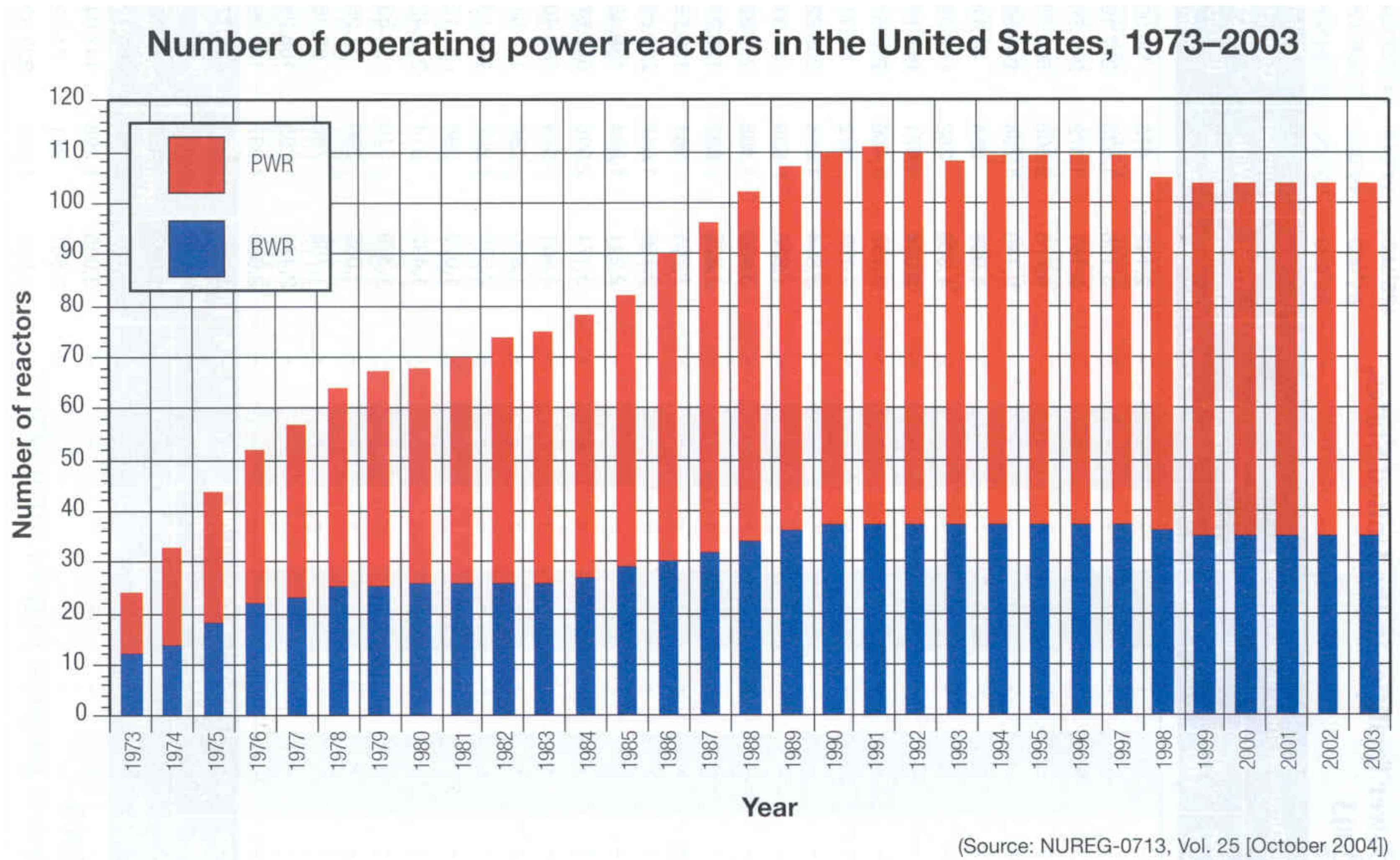
Source: Sproule Associates Ltd.

Generating costs are high. Gas fuelled plants lie idle $\sim \frac{2}{3}$ of the time.

US Power Plants. No orders since 70s

Nuclear Science & Engineering

Red: PWR, Blue: BWR years 1975-2003

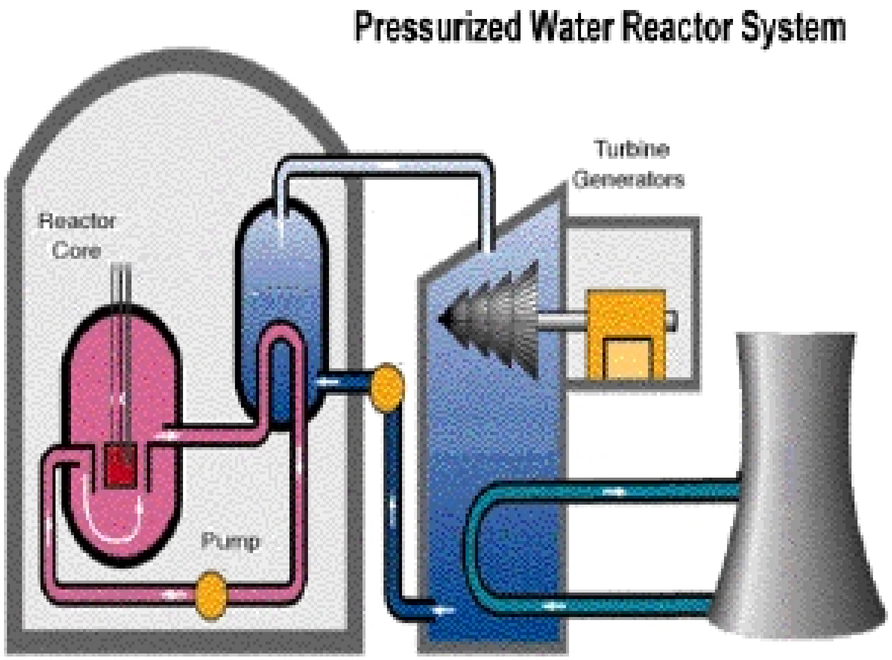


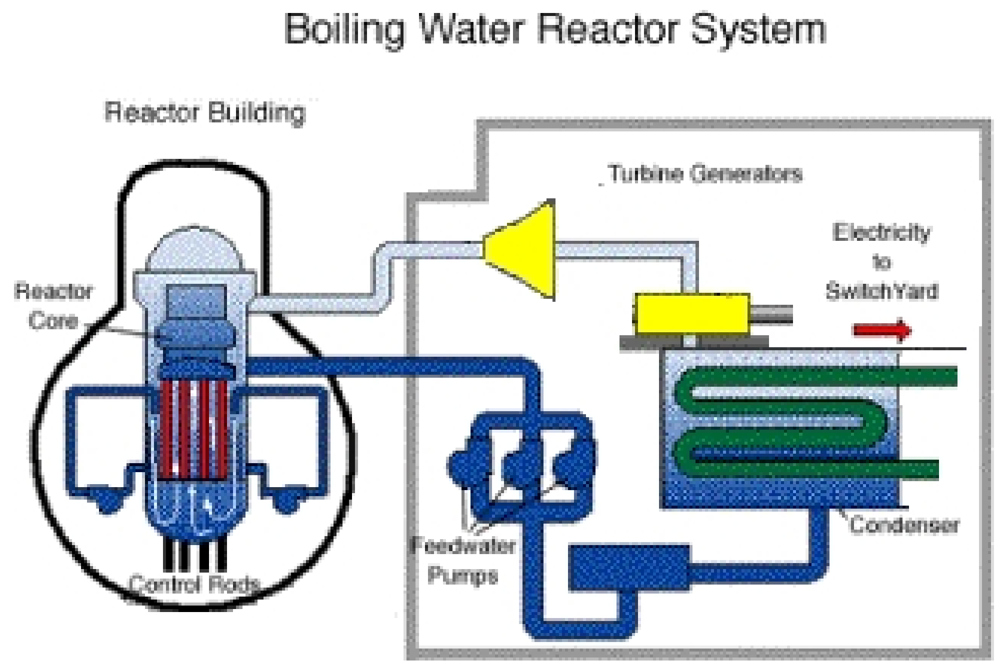
Nuclear News, Mar 2005

Total power plant numbers static (or decreasing)

But... 20 to 30 **specific** new reactors now under active consideration.

Light Water Reactor Types





Separate cooling and turbine loops

Turbine steam generated in core loop.

Other Present-Generation Reactors (mostly non-US)

Heavy water: CANDU

Graphite Moderated, water cooled: RBMK

Gas: Magnox, AGR, HTGR, PBMR

Fast: LMR (2 Russia, 1 Japan)

Limitations and Challenges

Limitations: Fuel Resources

Uranium: 'Sustainability'

Known resources ~ 4 Mt (@ < 130\$/kgU). But likely $\sim 10\times$ greater.

Once-through burn-up, current rate: ~ 50 GWd/MTIHM

("gigawatt-days per metric tonne initial heavy metal" – thermal, enriched).

Once-through usage rate at current world capacity ≈ 0.07 Mt/yr.

Resource time constant (resource/usage-rate) : 60 (to 600) years.

Uranium prospecting has not been exactly a California Gold Rush!

Uranium supply is not currently a significant contraint (hence breeders are not economically competitive). In the long term it will become an issue, especially if nuclear energy substantially expands.

Uranium in sea water: 4Gt (@ 3.3 parts per billion).

But... "Oceanic water pumped through the main condenser of a seaside reactor contains only about 5% of its natural uranium requirement."

Estimated recovery cost \$200/kg(?) is perhaps 4 times present terrestrial.

Fission Challenges

Safety, Economics, Proliferation, Waste

Safety is job #1. Continued excellent record is essential.

The US statutory approach depends on the Nuclear Regulatory Commission, which is the body that develops and enforces regulations.

Probabilistic risk assessment was largely developed by the Nuclear Engineering profession, and is now applied more widely.

Risk informed regulation.

use PRA to identify predominant risks, key components,
hence determine where to put attention/resources.

Economics: the mechanism to implement free society's priorities

Levelized cost of electricity

Source	Circumstances	$/MWh
Nuclear	First new, No Policy Help	47-71
Nuclear	First new, Policy Help*	32-50
Nuclear	Following plants, No Policy Help	31-46
Coal	Current policies	33-41
Coal	Greenhouse policies	to 91
Gas	Early 2004 conditions	35-45
Gas	Greenhouse policies	to 68

*Loan guarantees, Accelerated depreciation, Investment tax credit.

"The Future of Nuclear Power", MIT, 2003. "The economic future of nuclear power", U Chicago, Aug 2004

Capital cost the major component of Nuclear's challenge.

MIT Study base assumption: $2/W. [e.g. $2G for 1GWe plant.]

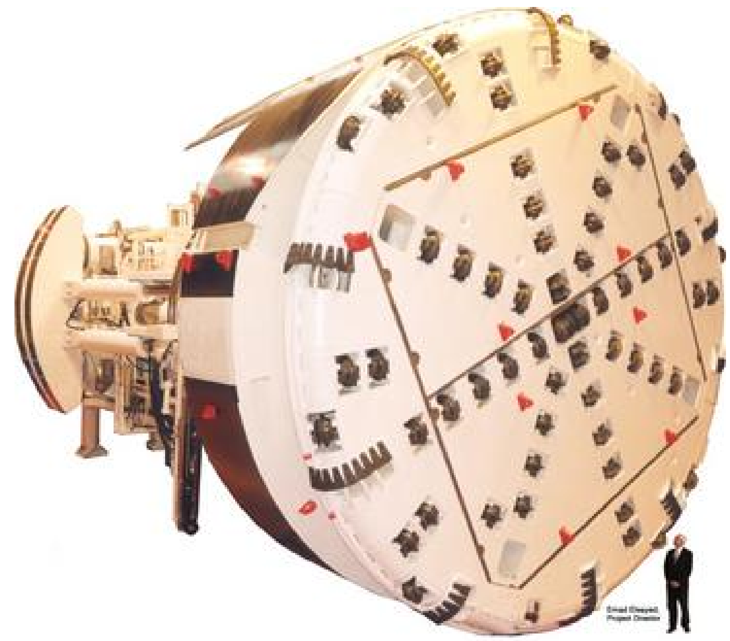
Being addressed by simplification, modularization, construction acceleration.

Capital cost will surely also be fusion's economic challenge.

Hydro Power Increases Limited and Costly

Addition of 183 MW average generation to Adam Beck, Niagara Falls, Ontario.

Began boring 5 Sep 2006.



New 10km, 14.4m dia tunnel.

Project construction cost \$985M: equivalent to \$5/W = >2.5 times new nuclear.

[source: http://www.waterpowermagazine.com/storyprint.asp?sc=2031375]

For hydro, like nuclear, the main costs are capital.

Proliferation

Perhaps the most influential factor in public opinion.

Presidential candidates' number one foreign policy challenge.

Once-through fuel cycle policy (Carter) was motivated by belief (unfulfilled) that other countries would follow suit.

One, perhaps more promising, proposal to discourage proliferation:

Major nuclear nations lease fuel "free" for power production in other nations.
Guaranteed by international agency/treaties.
On condition that materials remain under international control.

It is crystal clear that the US forgoing nuclear power generation will not promote the cause of non-proliferation. It is probably the opposite.

Fusion is not free of proliferation risks, because its neutrons could be used to breed weapons material. However, at least fusion does not depend on production of fissionable materials, so it definitely has some major advantages.

Spent fuel and Waste Disposal

Waste disposal for nuclear power is paid for already by the industry (¢ 0.1/kWh).

Fund income $\sim$ 0.7 \$G/yr. Federal government is in default of law.

Spent fuel currently accumulating in dry storage casks.

Yucca Mountain

Technology established.

Politics is challenging.

The "better" can be enemy of the "good" — or can be used to undermine it.

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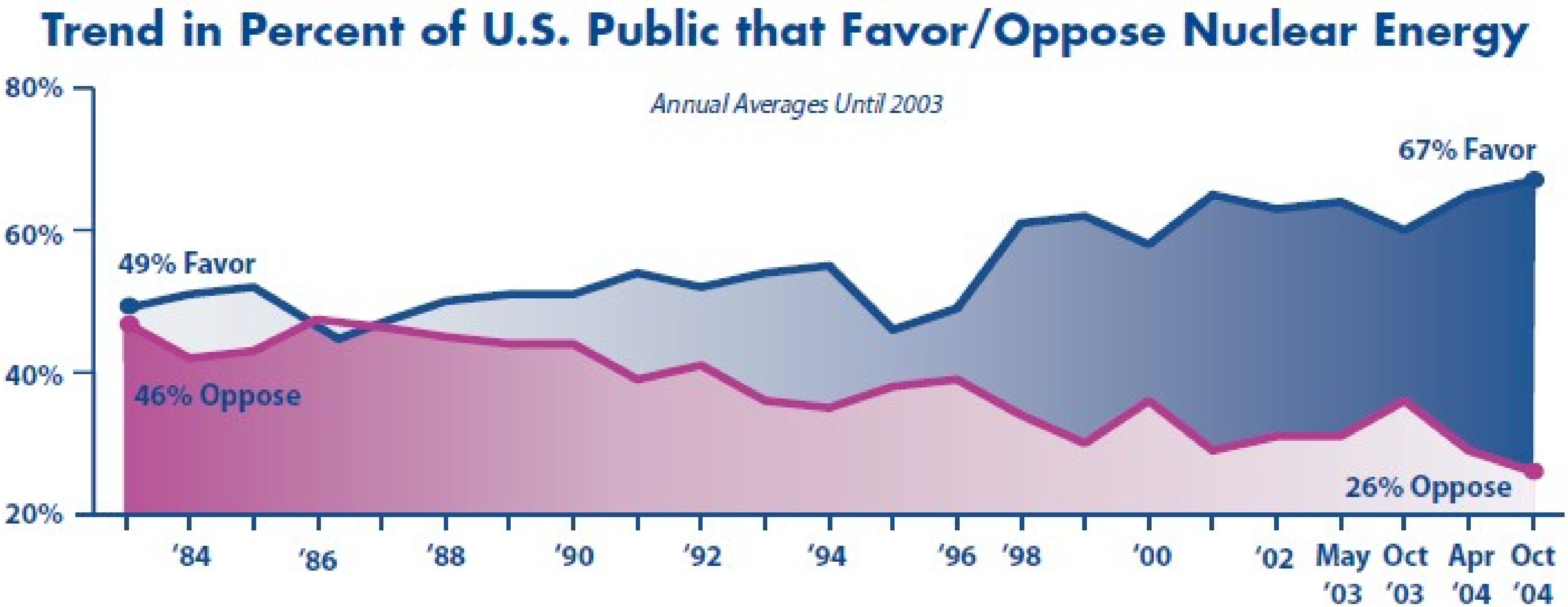
This is nobody's back yard!

Public Opinions Change



NEI Perspective on Public Opinion, Feb 2005

Question: [Apr 2001 %]	Agree	Strongly	Somewhat	Disagree	Strong	Some
We should keep the option to build more nuclear energy plants in the future	73	34	39		10	13
We should definitely build more nuclear energy plants in future.	66	31	35		12	18

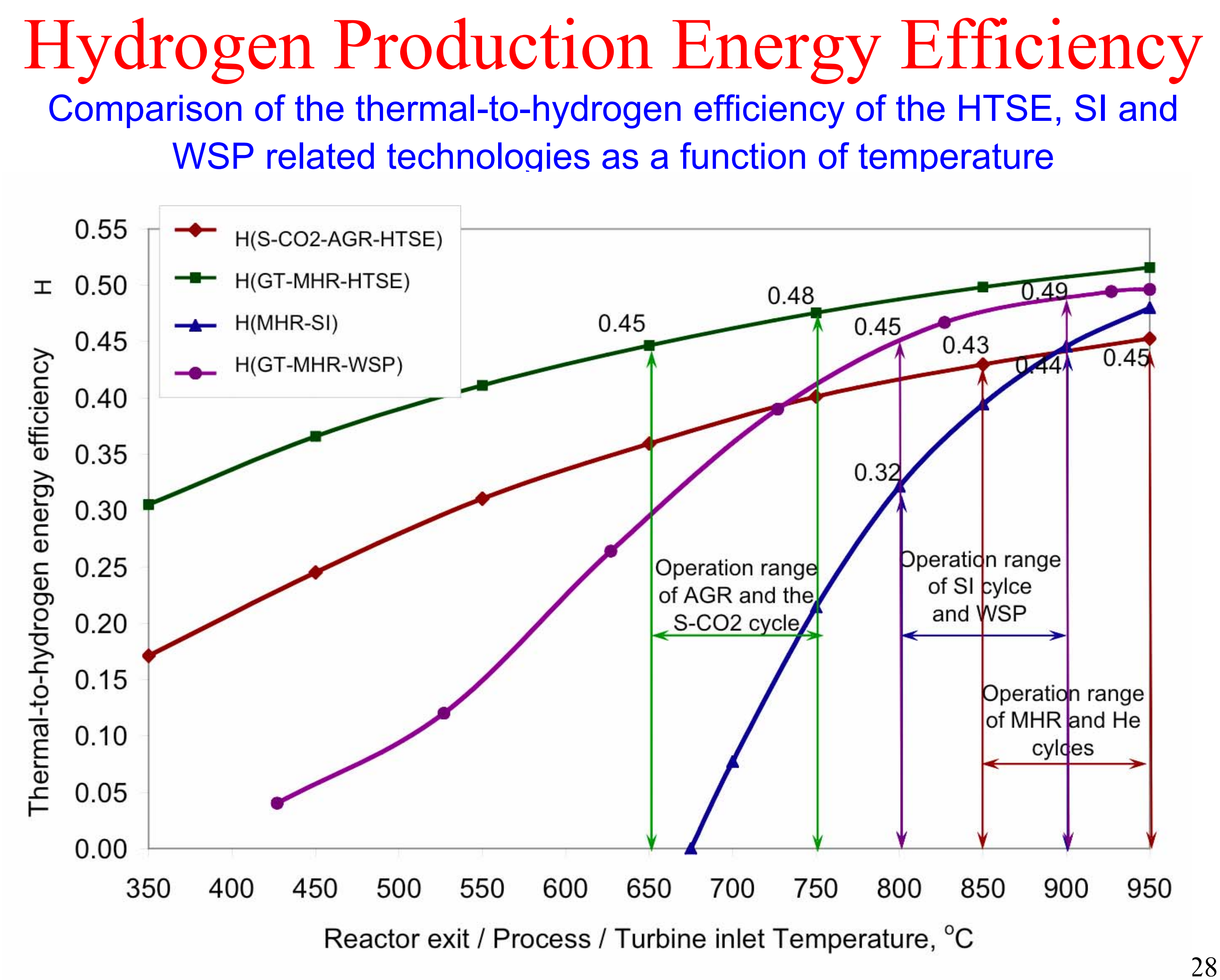
- Undergraduate student interest in nuclear is up by $\times 3$ nationwide.

Research and Technical Opportunities

Hydrogen: an Energy Vehicle, not Source

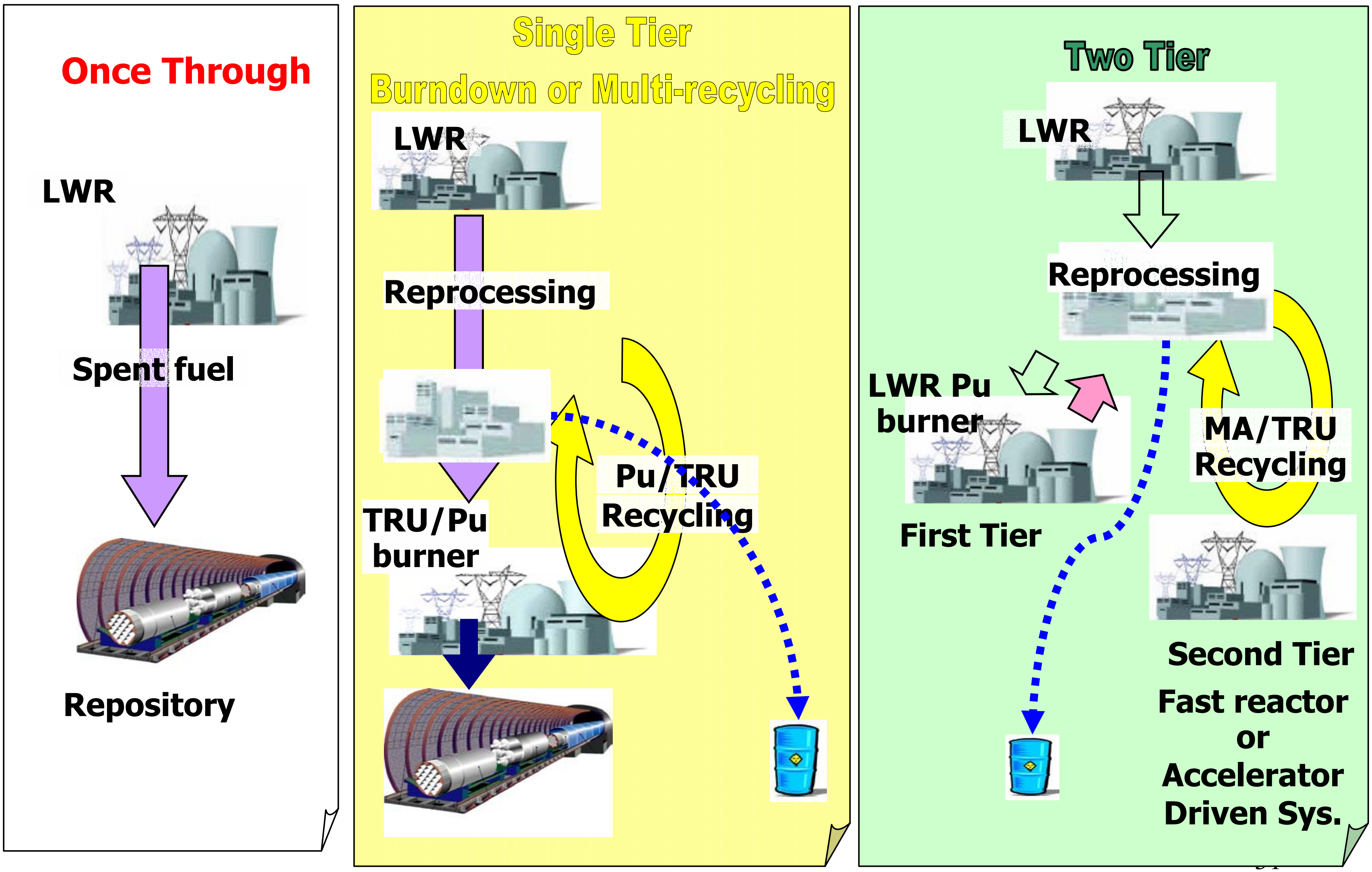
To realize environmental benefits it must be produced without emissions

Nuclear hydrogen: a natural synergy of high temperature technologies



Materials for high temperature operation a major challenge.

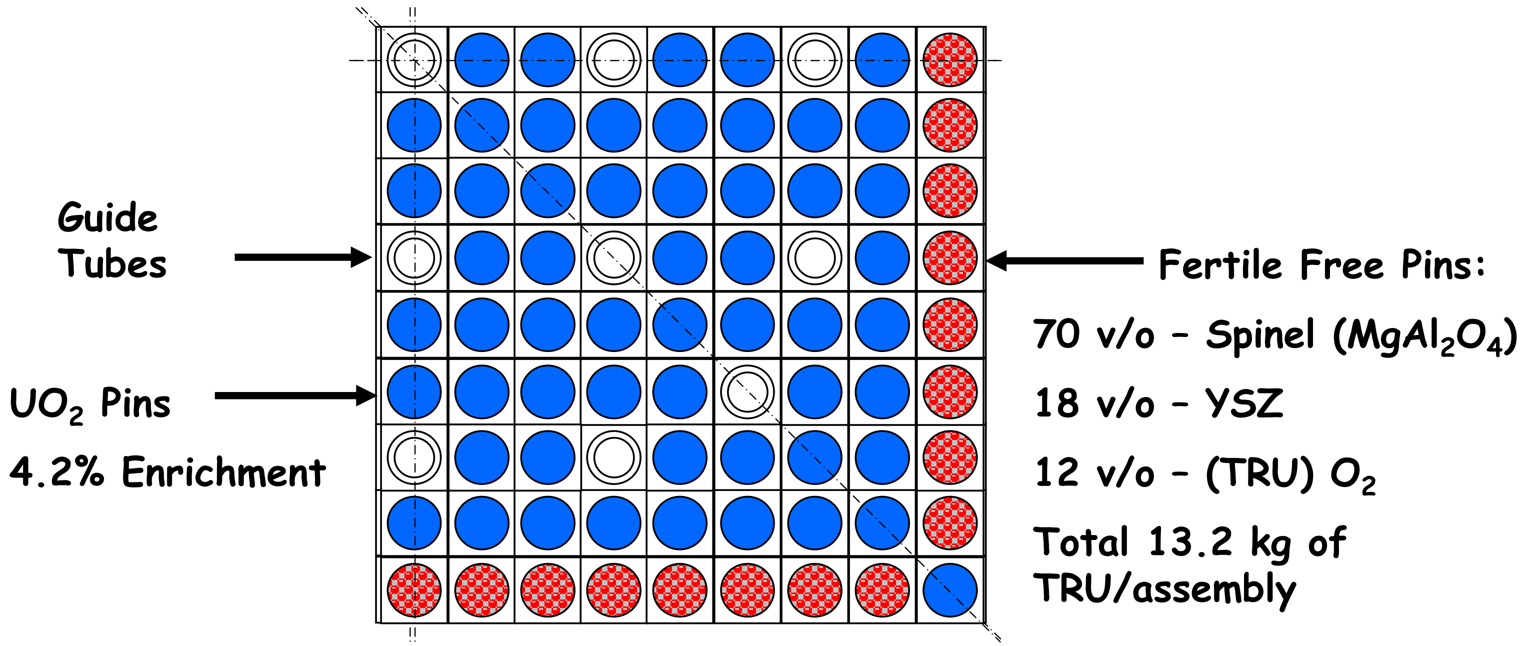
Fuel Cycle Options



TRU=Transuranics, MA=Major Actinides, LWR=Light water reactor, Pu=Plutonium.

The CONFU Assembly Concept

Combined Non-Fertile and UO_2 Assembly



- ***Multi-recycling of all transuranics (TRU) in fertile free pins leads to zero net TRU generation***
- ***Preserves the cycle length, neutronic control and safety features of all uranium cores***

"Optimization of the LWR Nuclear Fuel Cycle for Minimum Waste Production", E. Shwageraus, M.S. Kazimi and P.Hejzlar, CANES, MIT (2003)

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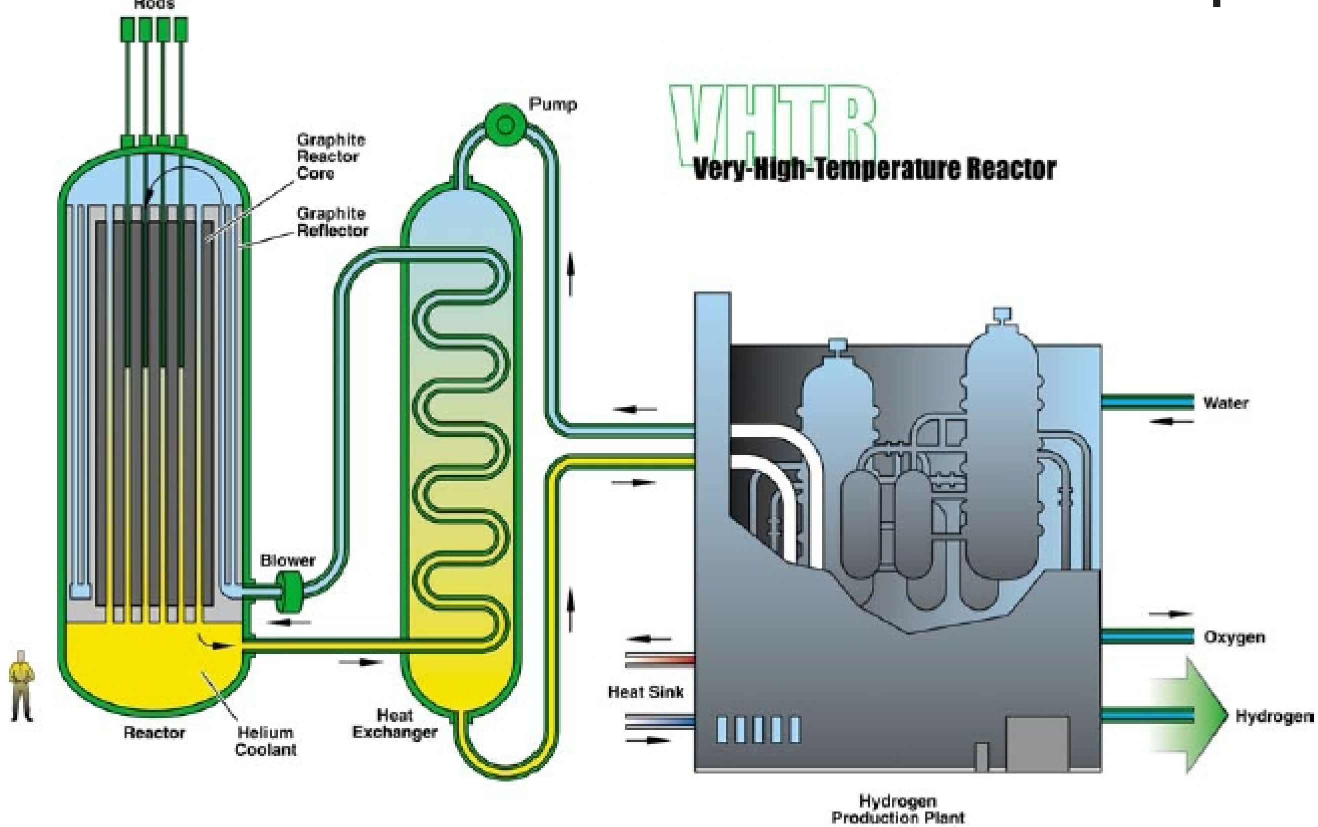
Replace some fuel pins with 'recycle' pins. Greatly reduce repository burden.

Generation IV Reactor Development (GIF)



- Sustainability
- Economics
- Safety/Reliability
- Non-Proliferation

VTHR

Supercritical-Water-Cooled Reactor	SCWR	Efficiency, simplicity
Very-High-Temperature Reactor	VHTR	H_2, Efficiency, Pebble/Prism
Gas-Cooled Fast Reactor	GFR	Hi-T, H_2, Actinide Recycle
Lead-Cooled Fast Reactor	LFR	Recycle, Long life, "Battery"
Molten Salt Reactor	MSR	Liquid fuel, Recycle
Sodium-Cooled Fast Reactor	SFR	Waste Management, Breeding

Nuclear Renaissance

Nuclear Energy never died; but growth in the US has waited for regulatory restructuring and social reprioritization.

Challenges remain. Many are sociopolitical: economic, safety, non-proliferation, waste disposal. Technical developments can help these, and many important research opportunities exist.

There is no technological magic bullet for energy or the environment.

There are important choices that will make sustainable energy possible.

Thoughtful people from all perspectives now realize that nuclear energy has a crucial role to play.

This is already leading to a resurgence of the nuclear industry in the US and its further expansion globally.