Nuclear Power: Status and Trends

The Diablo Canyon NPPT produces CO₂-free electricity at half the state’s (CA) average cost (2¢/kwh)
I. Introduction: Energy Demand and Outlook

II. Principles of Energy Generation from Nuclear Fission
   ▪ Fission chain reaction and reactor control
   ▪ Open fuel cycle

III. Strategic Issues for Nuclear Power

IV. New Nukes: Advanced Nuclear Energy Technologies
   ▪ Gen IV reactors
   ▪ Closed fuel cycle

V. Conclusion: Nuclear Power in a Sustainable Energy Future
Introduction: World Energy Outlook

**Predictions** (IEA)
1: World (US) demand up by +50 (28)%  
   (25y: $20T, U.S. >$5T)  
   Now : 450 Quad Btu/a → 2030: 680 Quad Btu/a
2: Redistribution Industrial World vs. Developing World
   40 Bbloe/a (220 GJ/a) vs. 6 Bbloe/a (34 GJ/a))

**Boundary conditions**
1: Disappearing resources (IEA)
   Now, or soon: beyond peak oil
   > 2050(??) peak gas, but unconventional gas (shale)
   > 2090(??) peak uranium ($^{235}$U)
2: Mitigate anthropogenic pollution
   Improve energy efficiency
   Reduce GHG emissions (fossil fuels)
   Alternative energy sources (renewables, nuclear)

3: US energy security/independence in global context !?
How to manage significant increases @ Boundary conditions?

Moderate growth potential of individual technologies → need diverse energy portfolio
Energy Demand (US)

100 Quad Btu/a = 49 GJ/a

Primary energy consumption (quadrillion Btu per year)

History
- Renewables (excluding liquid biofuels)
  - 2009: 7%
  - 21%
  - 25%
  - 1%
  - 37%
  - 9%

Projections
- Coal: 21%
- Natural gas: 24%
- Liquid biofuels: 3%
- Oil and other liquids: 33%
- Nuclear: 8%

EIA: Annual Energy Outlook 2011
Present Energy Demand (U.S.)

450 Quad Btu/a = 220GJ/a

U.S. uses 25% of total global energy demand, 65% imported (Canada, Mexico,.., Middle East)

Oil & nat. Gas & Coal 95%

Main Energy Uses:

- Industry
- Transportation (liquid fuels)
- Agriculture
- Commercial & public
- Residential

Growth potential | bound. cond’s.

→ Nuclear Energy: high power density, scalability, economics
Trends in Nuclear Energy Production

Steady increase of nuclear power output over past 20 years. Now equivalent: 24 quads of oil

World (US)
443 (103) reactors
365 (100) GW

World
53 new reactors,
US: 3-4,
> 20 planned,
license applications

US potential:
several new reactors/a
(@ $(2-3)B/GW_e, \rightarrow 5¢/kWh)
Nuclear Fission Energy in the U.S.
Status and Trends in Technology

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Nuclear Rearrangement Energies

\[ M_{(N,Z)} < N \cdot M_n + Z \cdot M_p \rightarrow \Delta M \square B(A=N+Z) \]

**Einstein**: equivalence

mass = energy \[ E = M \cdot c^2 \]

In assembly of a nucleus \( B=\Delta M c^2 \) is released to outside

Energy release in fission \( A \rightarrow 2A/2 \)

\[
\begin{align*}
M(\text{235}U) &= 47 \text{ mg} \\
\Delta M &= M \times 10^{-3} \\
\text{fission} &\rightarrow \Delta E = 47 \mu g \cdot c^2 \approx 4 \cdot 10^9 \text{ J} \\
M(\text{TNT}) &= 1 \text{ t} \\
\Delta M &= M \text{ combustion} & \Delta E \approx 4 \cdot 10^9 \text{ J}
\end{align*}
\]
Nuclear Fuels

Enrichment for fuels $\rightarrow$ 3-4 % fissile
Enrichment for weapons $\rightarrow$ >90 % fissile

W. Udo Schröder, 2011
Energy Generation from $n_{th}$-Induced Fission

$^{235}U + n_{th} \rightarrow ^{236}U^* \rightarrow 2 \text{ FF} + 2(3)n + 200\text{MeV}$

Example: $^{236}U^* \rightarrow 1^{17}La + ^{87}Br^* + 2n_{fast}$

Converts 0.1\% of the mass into energy

$1\text{g} \ ^{235}U/\text{day} = 1\text{MW}$

$10^8 \times$ chemical energies

$E_{\text{ff}} = 168 \text{ MeV}$

$E_{n \text{ tot}} = 5 \text{ MeV}$

$E_{\gamma} = 7 \text{ MeV}$

$\text{FF } \beta \text{-decay} = 27 \text{ MeV}$

$Q_{\text{total}} = 207 \text{ MeV}$

Neutrons per fission:

$k = 2.5 \pm 0.1$

$k=1 \rightarrow \text{critical } = \text{chain rxn}$

$k>1 \rightarrow \text{explosive chain rxn}$

Fission neutrons are fast:

$n$-energies $<E_n> \approx 2 \text{ MeV}$

$\rightarrow$ Fast $n$’s do not induce $^{235}U$ fission $\rightarrow$ need moderation

Most fission neutrons are lost and/or not useful for further fission

Fission fragments = reactor poison, stop chain reaction. $k < 1$ !!!
Thermal-n Induced Fission Chain Reaction

Neutron multiplication through fission \( k=2.4 \), minus losses (capture, leaking,..), \( \rightarrow \) effective \( k < 2.4 \).

One n used in fission \( \rightarrow \) effective multiplication \( k-1 \):

\[
\frac{dN_n}{dt} = \frac{1}{\tau} (k-1) N_n \rightarrow
\]

\[
N_n(t) = N_n(0) \cdot e^{(k-1)t/\tau}
\]

\( k >1 \): avalanche of n
\( \tau = \) time betw. generations
\( (\tau \sim 40\mu s \text{ in reactors} \quad \tau \sim ns \text{ in explosives}) \)

\( k_{\text{eff}} = k_{\text{prompt}} + k_{\text{delayed}} \)

**Reactor Control**

\[
T = \frac{\tau}{(k_{\text{eff}} - 1)}
\]

\( k_{\text{eff}} \approx 1 \) e.g., \( k_{\text{eff}}=1.03 \)

---

Most fission neutrons are lost and/or not useful for further fission
Fission fragments = reactor poison, stop chain reaction. \( k < 1 !!! \)
Neutron Moderation

Fission neutrons too energetic, “thermalize” to maximize $\sigma_f$ for $^{235}$U

→ multiple elastic scattering (“moderation”) moderator: small $\sigma_{\text{capt}}$!

Need: $2 \text{ MeV} \rightarrow 0.025 \text{ eV}/2\text{MeV} = 10^{-8}$

Need to “miss” $^{238}$U capture resonances ($2\text{eV} < E_n < 10\text{keV}$)

$\text{H}_2\text{O}, \text{D}_2\text{O}, \text{Be, C(graphite)}, \text{prevent leakage}$

$H, D$ are best moderators

$H + n_{\text{th}} \rightarrow D + 2.2 \text{ MeV}$
Principle Boiling Water Reactor

- A: Containment Structure
- B: Control Rods
- C: Reactor
- D: Steam Generator
- E: Steam Line
- F: Pump
- G: Generator
- H: Turbine
- I: Cooling Water Condensor
- J: Cooling Tower
Passive safety:
Pressure reactor vessel ~1’ thick steel, pressure tubes,
Reactor containment building with several 3-4 foot thick concrete walls, concrete + water shielding on top of reactor vessel, gravitation replaces mechanical pumps.

Fail-safe operation
Negative Reactivity

Negative feedback loops:
Reaction subsides when
- coolant gets too hot or disappears (less dense, less moderation)
- fuel gets too hot ($n$ capture increases)
- control rods are not moved out

2-3 B$/NPPt
Nuclear Fuel Storage & Transport
Uranium Fuel Cycle

1000 MW of electricity for one year

800,000 tons Ore

250 tons Natural uranium

35 tons Enriched Uranium (Costly Process)

215 tons depleted uranium - disposal plans uncertain

Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

35 tons Spent Fuel
Yucca Mountain
(-10,000 years)
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products

Within 10 years, 93% of fission products are stable and can be partitioned and sold.

200 tons Ore

1 ton Natural Thorium

Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned"

1 Ton Fission products;
- no uranium, plutonium, or other actinides

The remaining 17% fission products go to geologic isolation for ~300 years.
Radio toxicity vs. time after shutdown, of spent fuel from

- pressurized water uranium reactor (PWR),
- U/Pu breeder, and
- Th/U fuel cycle.

FP indicates the faster decay of fission products.

Multiple reprocessing, less residuals.

Reprocessing involves robotics because of $^{210}$Th gamma radiation → not for extremists’ garage!

(David, Nifenecker, 2007)
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V. Conclusion: Nuclear Power in a Sustainable Energy Future
1. Operational reactor safety ...................................................... ✓
2. Resource limits of nuclear fuel ($^{235}$U/Pu, Th,...) ... ✓
3. Safe capture, storage and sequestration of radiotoxic nuclear waste ................................................................. ✓
4. Proliferation resistance (nations, individuals) ..... (√)
5. Economy (Capital plus fuel costs) ................................. ✓
6. R&D requirements ................................................................. ✓
7. Capability for rapid deployment ........................................ (√)
8. Public perception ................................................................. (√)

Paul Sherrer-Institute/Switzerland.
Omitted: large hydro disasters Shimantan and Banqiao (China 1976: 26,000†).

2006 U.S. coal mines : 42† (equivalent 1 Chernobyl nuclear accident/a)

Every primary energy technology has potentials & hazards.
→ Safety record of nuclear energy
Pollution Footprints of Energy Technologies

Greenhouse Gas Emissions from Electricity Production

Source: IAEA 2000

High power density → small environmental footprint → Nuclear

GHG (fossil): CH₄, CO₂, NOₓ, SOₓ, H₂O

Other (fossil): Particles PM₂.₅,

Metals (coal, oil): (Be, ..., Hg, U, Th)

Chemical toxins (Solid-state PV)

Radiotoxins (99% from coal, airbn: 80-100 t U/a)

nuclear fuel residues: Fiss Frgm, Min Actind, localized + decays)
The following few slides provide an overview of the Fukushima event (March 11, 2011) in Japan, where earthquake and subsequent tsunami disabled several nuclear power plants, leading to a release of significant amounts of radioactivity into the environment.

Lessons taken from this event will have consequences for the design criteria imposed on future nuclear power stations, as indicated by reports of government commissions and independent expert conferences.
Fukuchima-Daiichi NPP

Fukushima BW Reactor Design (GE & Toshiba)

Note: absence of containment around the spent-fuel pool.
What Went Wrong, Hydrogen Explosion

Nuclear fuel rods clad in Zr alloys (little corrosion, low capture cross section).
But: reactivity against water
\[ \text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2 \]

- Operators vented H into the maintenance hall of 1,2,3 \( \rightarrow \) H\(_2\)/O\(_2\) mix detonated. Direct venting of H\(_2\) into atmosphere would have been preferred design option.
- More modern reactors have a catalyst-based recombinator hydrogen and oxygen into water at room temperature before explosivity limit is reached.

While a similar event would not have happened with the modern U.S. stations, there is an obvious need for more comprehensive risk/benefit analyses for all stations.
There have been no fatalities in the Fukushima event caused by radioactivity.

Close vicinity of the Fukushima NPP is polluted by radioactivity released in the $\text{H}_2$ explosions. Clean-up of affected areas may take years and $$.

Fortunately, polluted area is small.

For comparison, look at environmental footprint of renewable energy technologies, e.g., wind farms.
Wind Farm “Energy Sprawl”

Requires large area (coastal strip 67 mi x 8 mi for $P \approx 1\text{GW} + \text{NPP}$ on standby ($P/P_{\text{max}} = 0.2$)) → **Permanently uninhabitable.**
Radio toxicity vs. time after shutdown, of spent fuel from

- pressurized water uranium reactor,
- U/Pu breeder, and
- Th/U fuel cycle.

FP indicates the faster decay of fission products.

Multiple reprocessing, less residual waste.

Transmute/incinerate transactinides and FF solves waste issue.

Store very small amounts of HL waste for ~100 years
small geological depository, problem disappears in time.

Successful long-term test depository in Carlsbad maintained by U.S. armed forces.
World (US)
443 (103) reactors
365 (100) GW

U use: 67 kt/a
World reserves: 5 Mt known (15 est.)
Once-through cycle: 200 years

Reprocessing: \( \sim 10^3 \) years
US: 174 t weapons grade U for fuel mix

Th use: little so far
World reserves >15 Mt \( \sim 10^3 \) a
with reprocessing.

Gen IV breeder reactors,
Thorium reactors, molten salt reactors
Issue: Deployment Potential

Can we double nuclear capacity over 25 years?

100 GW/25y = 4 GW/a = (2-3)NPPT/a \( \rightarrow \) requires $(8-10)B/a = 12,000$ construction workers continuously. + 2500 operators/a

Past performance:
Construction dates of reactors still operating ($GW_e$ vs. year).

1985: France built (completed) 2.5 GW/a

Construction time now 2 years/NPPT

Japan, Korea, China

Operator manpower

D. McKay: *Sustainable energy without the hot air*, 2009
Can we afford to invest long-term $10 B/a into nuclear energy infrastructure? (Can we afford not to??)

→ Economic necessity, global growth high-tech industry

→ No strategic problem, except political and regulatory
  Economics of scale for standardized, modular NPPT

  - Loan guarantees
  - Combined licensing for construction and operation
  - Limit number of standardized, safe reactor designs
  - Mass fabrication of modular designs (combine for size)
  - Integrated self-contained modules (on site disposal)
Strategic Issue: Nuclear Proliferation

At present, nine countries have developed and possess nuclear weapon stockpiles, each in the proclaimed interest of national security. In fact, for a nuclear-armed country the presumed retaliation for a first-strike nuclear attack on another nuclear country is a strong deterrence of such use and of war-like conflict resolution in general.

And perhaps for these reasons, despite much international tension and a number of armed conflicts, in 63 years the U.S. has remained the only nation that has ever engaged in nuclear warfare. This action was taken in an epoch when nuclear retaliation was not an option for an adversary. " (from the above report)
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Timeline of Advanced Reactors/Fuel Cycles

GNEP framework (now includes U.S., U.K.) →
2030: Gen IV designs studied, modelled, tested:
• Very high-temperature reactors (VHTR)
• Sodium-cooled fast reactors (SFR)
• Reactors cooled by supercritical water (SCWR)
• Lead-cooled fast reactors (LFR)
• Gas-cooled fast reactors (GFR)
• Molten-salt reactors (MSR, LIFTR)

Already testing Gen IV: France, Japan, S-Africa, China, India

Operational reactor safety;
Resource limits of nuclear fuel ($^{235}$U/Pu);
Safe capture, storage, sequestration of radiotoxic waste;
Prevention of proliferation of nuclear materials for weapons;
Economy of nuclear energy.
Advanced Reactors: Pebble-Bed HTR

S-Africa, China: Modular (@250MW)

He (inert gas) cooled
T ~ 950°C
C-moderator/reflector

Continuous throughput replacement of “pebble” fuel elements

Strongly negative reactivity

Core has high surface/volume ratio, low power density.

Fail-safe operation.
Small Modular Reactors

Prefabricated (GE A-1000 conventional PWR comes in 300 parts)
Few standardized reactor designs.
Autonomous operation:
without human interference,
self-fuelling (traveling wave) U or Th fuel

Babcock-Wicox modular reactor
Could run on Th
Hyperion 200 MW U/He
Transmutation/Breeding in ADS

Spallation: $n$ multiplication $\rightarrow$ incineration of waste generates E

Advanced (ADS) reactor development under GNEP program

Yucca Mountain = overkill
Much more than needed with reprocessing
Fuel Breeding $^{239}\text{Pu}/^{233}\text{U}$ Breeding

Technologically understood, several working research/test reactors
Fast (neutron spectrum) U reactor: $n$-capture without fission

\[ ^{238}\text{U} + n \rightarrow ^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} (2.4 \cdot 10^4 \text{a}) \]

Prevent additional $n$ capture

$+$ $n \uparrow$ $+$ $n \uparrow$

Continued $n$ capture/\(\beta\) decay

\[ ^{239}_{94}\text{Pu} + n \rightarrow ^{240}_{94}\text{Pu} \rightarrow ^{241}_{94}\text{Pu} \]

Isotope mix: Not useful for nuclear fuel/weapons $\rightarrow$ extensive isotope separation

Need many neutrons: source is unimportant!
(Use waste or heavy materials like Pb, Bi,...)
Technologically understood, several working research/test reactors
Fast (neutron spectrum) U reactor: $n$-capture without fission

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India builds Th reactor fleet $\rightarrow$ large Th resources, small waste problem. (Mumbay test reactor). Also France, Russia
Uranium Fuel Cycle vs. Thorium

1000 MW of electricity for one year

800,000 tons Ore

35 tons Enriched Uranium (Costly Process)

Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

215 tons depleted uranium - disposal plans uncertain

35 tons Spent Fuel

Yucca Mountain

(-10,000 years)

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(David, Nifenecker, 2007)
Conclusion: Nuclear Power in a Sustainable Future

Promising and potent: Advanced nuclear power, redirection of electricity generation mainly to nuclear. Develop synfuels from coal/nat. gas. Need massive renewal of energy infrastructure

**Develop and Employ Advanced Nuclear Power in the US:**

- Continue to improve the safety of nuclear reactors and processing plants.
- Test/construct advanced modular nuclear reactors @ sites of existing plants.
- Test/construct advanced burner/transmuter → reduce radiotoxic waste.
- Import/develop closed nuclear fuel cycle technologies.
- Develop/test proliferation-safe reprocessing methods (e.g., UREX+).
- Test/develop a closed Th/U breeder fuel cycle.
- Develop ADS systems, high current accelerator technology.
- Develop the chemistry of molten salt mixtures, molten salt test reactor.
- Expand the radio-chemistry of actinides, transactinides and fission products.
- Operating a semi-permanent nuclear waste depository, flexible strategy.
- **Train personnel in nuclear and radiation technologies!**
End