The Looming Energy Crisis and Global warming: Is Nuclear Power the answer?

Wednesday, August 02, 2006 Hartford Courant

Romualdo deSouza, Indiana University
Growing global energy needs!

With oil and natural gas prices expected to continue rising, coal is an attractive fuel for nations with access to ample coal resources ... In particular, the United States, China, and India are well-positioned to displace more expensive fuels with coal, and together the three nations account for 86 percent of the expected increase from 2004 to 2030.
Different sources of energy: Ethanol (Biofuels)

29% more fossil energy to turn corn into ethanol than the amount of fuel the process produces.

Switch grass 45%
Wood 57%

“Ethanol production in the US does not benefit the nation’s energy security, agriculture, economy, or environment”

--- David Pimentel, Cornell University and Tad Patzek, UC, Berkeley
Hydrogen as a source of energy: Is it really?

Hydrogen while plentiful in the universe, is found on earth in compounds. To produce H₂, we need to liberate it from these compounds. Bond breaking takes energy!

Hydrogen is best viewed as a storage medium.
Global Warming (Climate change)

One piece of evidence – correlation between CO₂ levels in Vostok ice core and temperature change
Global Warming (Climate change)

Need to limit man-made generation of CO$_2$ i.e. limit combustion of carbon containing fuels.

http://www.grida.no/climate/vital/07.htm
Development of nuclear power by other countries

China going nuclear in a big way

1. By 2020, China expects nuclear to grow from 2.3% to 4%. To meet that goal it must build 2 facilities every year!

2. By 2060, there are plans to have 1/3 of China’s power supplied by nuclear power.

3. Nuclear power facilities are being concentrated in heavily populated, industrialized areas where high levels of pollution exist.

4. Concentrating on fast reactor technology that improves efficiency of uranium usage by factor of up to 70.

As energy shortages threaten economic boom, nation races to expand industry

QINSHAN, China — The shadows of Chernobyl and Three Mile Island no longer reach to the pine-crested hillsides of Hangzhou Bay, where China is rushing to expand a nuclear power station to meet soaring demand for electricity for its economic boom. Driven by crushing fuel shortages, stinging ambitions to profit from its hard-won nuclear prowess, Beijing has embarked on a quest to more than double its nuclear power generating capacity by 2020.

The push for more nuclear power means opportunities for U.S., French and Russian technology suppliers that are competing for up to $8 billion in contracts for two new nuclear power plants — the biggest deals in years for the industry.

The French nuclear group AREVA, Russia’s Atomstroyexport and Westinghouse Electric Co. — the U.S. unit of British Nuclear Fuels PLC, which Japan’s Mitsubishi Heavy Industries has offered to buy — are awaiting Chinese decisions on bids for facilities at Sanmen, in the eastern province of Zhejiang, and Yandong in Guangdong province, which borders Hong Kong.

“We are fully committed to transferring our advanced nuclear technology to China,” Paul Feilen, a senior vice president of AREVA’s Framatome unit, said at a recent conference in Shanghai.

At Qinshan, a two-hour drive southwest of Shanghai and its 20 million residents, sites are being prepared for four new reactors. In addition to the five already operating at three different facilities.

“The excavation is almost finished,” said Yang Lai, general manager for Qinshan Phase II, China’s showcase for domestically developed nuclear technology and equipment. He pointed out the window to a site cleared and waiting for construction to begin.

No fears of a Chernobyl

Yang and other executives at Qinshan speak of nuclear power with the conviction of true believers.

They point to China’s own accident-free record after 14 years of nuclear power generation. And they say technology has advanced far beyond that used decades earlier, when the 1979 partial meltdown at Three Mile Island nuclear plant in Pennsylvania and the 1986 explosion at the Chernobyl plant in the Ukraine decimated public support for atomic energy in the West.

A worker stands in front of a control monitor June 10 at the Qinshan No. 2 Nuclear Power Plant.

China’s nuclear program, dating back to the 1950s, began commercial operations only in 1991, at Qinshan.

For six years, beginning in 1995, dozens of potential projects put on hold amid public anxiety over excess capacity, safety and the relatively high costs of nuclear-generated electricity.

The race to build more plants resumed last year, as China struggled with blackouts amid its worst energy crisis in decades.

From the highest levels of Chinese government to the technicians running Qinshan and other plants, there is a newfound conviction that nuclear power is the most practical option for reducing the country’s reliance on heavily polluting coal-fired power plants.

“Build Nuclear Power, Boost the People,” says a slogan on billboards throughout the sprawling facility, built into a peninsula surrounded by farms and fishing villages.

China expects the share of its power supplied by nuclear generation to grow from 1.9% in 2020 from 2.3% today. To meet that, it must build about two new facilities every year.

“After 2020, nuclear power’s growth will increase much, much faster,” its importance in China’s energy framework will be indisputable,” Shen Wunian, vice chairman of China National Nuclear Corp.’s science and technology committee, said at an industry conference in Shanghai.

Shen showed a chart forecasting that by 2060, nuclear power could provide about a third of the country’s energy needs.

China is concentrating its nuclear power facilities in heavily populated, industrialized coastal regions, where demand and pollution levels are forcing local governments to burn coal.

“Much of the new nuclear power will be built in the south where they lack their heavy supply of coal,” says Philip L. Swanson, director of the center for Energy, Petroleum and Mineral Law and Policy at the University of Dundee, Scotland.

“Every country has the ability to resolve this problem.”

We have enough space to build it,” said Hu Haiyan, Communist Party boss for the Qinshan Nuclear Base.

Dealing with radioactive waste

Unlike other countries, China is proceeding over how to handle the radioactive waste from its plants.

Shen Wunian, vice chairman of China National Nuclear Corp.’s science and technology committee, said research was focusing on fast reactor technology that can reduce the amount of waste and boost efficiency of uranium usage by up to 10 times — a boon for China, which will eventually need to import most of the uranium it needs as its nuclear program expands.

Managers at Qinshan refused to say how much waste is stored there.

“We have enough space to build it,” said Hu Haiyan, Communist Party boss for the Qinshan Nuclear Base.

“Every country has the ability to resolve this problem.”

“We have enough space to build it,” said Hu Haiyan, Communist Party boss for the Qinshan Nuclear Base.

“Every country has the ability to resolve this problem.”

“We have enough space to build it,” said Hu Haiyan, Communist Party boss for the Qinshan Nuclear Base.

“Every country has the ability to resolve this problem.”

“We have enough space to build it,” said Hu Haiyan, Communist Party boss for the Qinshan Nuclear Base.

“Every country has the ability to resolve this problem.”

“We have enough space to build it,” said Hu Haiyan, Communist Party boss for the Qinshan Nuclear Base.
\[
\frac{A}{Z}X + ^1_0n \rightarrow \left[\frac{A+1}{Z}X\right]^* \rightarrow \frac{A^1}{Z^1}X^1 + \frac{A^2}{Z^2}X^2 + n^1 + Q
\]

**Bookkeeping:**

\[A + 1 = A^1 + A^2 + \nu\]
\[Z = Z^1 + Z^2\]
\[Q \approx 180 \text{ MeV} \approx 2 \times 10^{10} \text{ kJ/mole} \Rightarrow E_{\text{kinetic}} + E^*_1 + E^*_2\]

160 MeV

IF \(\langle \nu \rangle \geq 1\), chain reaction possible

20 MeV
The concept of cross-section

If we “throw” a neutron at a nucleus what is the probability that the neutron causes a nuclear reaction?

For a beam of neutrons:

\[ N = (I)(\sigma)(x) \]

N = reaction rate (reactions/s)
I = Intensity (particles/s)
X = target thickness (atoms/cm\(^2\))
\( \sigma \) = cross-section (barns)

1 barn = 1 b = 1 \times 10^{-24} \text{ cm}^2
<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Abundance</th>
<th>Cross-section (b) $\sigma(n,f)$</th>
<th>Ave. number of neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$</td>
<td>100%</td>
<td>$2 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>99.27%</td>
<td>$\leq 5 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.72%</td>
<td>577</td>
<td>2.44</td>
</tr>
<tr>
<td>$^{233}\text{Th}$</td>
<td></td>
<td>530</td>
<td>2.51</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td></td>
<td>742</td>
<td>2.89</td>
</tr>
</tbody>
</table>
Fuels

Only U and Th of nature's elements undergo fission readily.
Reaction cross sections largest for thermal neutrons (0.03 eV @ 300 K)

Are we going to run out of Nuclear Fuel?

Global Uranium Resources to Meet Projected Demand
Latest Edition of "Red Book" Predicts Consistent Supply Up to 2025
Staff Report
2 June 2006 (http://www.iaea.org/NewsCenter/News/2006/uranium_resources.html)

*Uranium 2005: Resources, Production and Demand* - also called the "Red Book" - estimates the total identified amount of conventional uranium stock, which can be mined for less than USD 130 per kg, to be about 4.7 million tonnes. Based on the 2004 nuclear electricity generation rate of demand the amount is sufficient for 85 years, the study states. Fast reactor technology would lengthen this period to over 2500 years.

However, world uranium resources in total are considered to be much higher. Based on geological evidence and knowledge of uranium in phosphates the study considers more than 35 million tonnes is available for exploitation.
Important concepts in a nuclear reactor

- Capture efficiency
- Critical Mass

Control the neutrons and you control the chain reaction
Capture efficiency

If the efficiency > 48% \(\Rightarrow\) explosion

If the efficiency < 48% \(\Rightarrow\) no chain reaction

If the efficiency = 48% \(\Rightarrow\) steady-state reaction = REACTOR

Note: Reactor can operate with lower abundance \(^{235}\text{U}\) if efficiency > 48\%
Critical Mass

1. $M_{\text{crit}}$ is the minimum mass necessary to achieve the minimum efficiency criterion; Geometry dependent

2. For a given geometry the surface to volume ratio is different. A larger surface area allows more neutrons to escape, hence is less efficient.

3. Critical conditions: $M \geq M_{\text{crit}}$

   $M_{\text{crit}} \sim 2$ kg for $^{235}$U; $R \sim$ baseball; $10^{15}$ d/sec
Reactor components

1. Fuel Rods: Energy Source
   - 3% enriched $^{235}$U in Zr-stainless steel rods
   - Rod design; 3% abundance make nuclear explosion impossible in a reactor
   - Fission neutron energy spectrum 0-5 MeV $\Rightarrow$ need to slow down neutrons

2. Moderator: Enhance efficiency (low A materials thermalize neutrons best; low $(n,\gamma)$ to avoid capture of neutrons
   - $\text{H}_2\text{O}$ (light water) -- $\sigma(n,\gamma)=0.333\text{b}$
   - $\text{D}_2\text{O}$ (heavy water) -- $\sigma(n,\gamma)=5.2 \times 10^{-4}\text{b}$

3. Control rods: Thermostat (regulation)
   - Maintain $P(\text{fission})/P(n,\gamma) \sim 1$
   - Control with neutron sponges (e.g. $^{113}\text{Cd}$ $\sigma(n,\gamma)=2 \times 10^4\text{b}$)
   - Inserting or removing the control rods reduces or increases the neutron flux and thus controls the fission rate

4. Coolant
   - Primary coolant – Heat exchange between fuel rods and secondary coolant ($\text{H}_2\text{O}$, $\text{D}_2\text{O}$, $\text{CO}_2$, $\text{He}$, $\text{Na}$)
   - Secondary coolant converts heat to steam
   - Designed to interact minimally with environment
Reactor components

5. Reactor Shielding
   - Low Z material to reflect neutrons that escape moderator back into reactor; concrete is cheap and effective.

6. Containment Shield -- Accident safeguard
   - Barrier against air and liquid escape both under routine and extreme circumstances (e.g. earthquake)
Sources of Neutron loss

1. $^{238}\text{U}$ capture: Cross-section $\sigma(n,\gamma)$ not large but 30 x more $^{238}\text{U}$ than $^{235}\text{U}$

2. Capture in reactor components: Need to use materials with low $\sigma(n,\gamma)$ and high resistance to radiation damage

3. Fission product poisons: Many fission products have high $\sigma(n,\gamma)$ and as these build up the reactor becomes less efficient (e.g. $^{136}\text{Xe}$ $\sigma(n,\gamma) = 3 \times 10^6$ b)

4. Neutron escape
Types of Reactors

Power reactors – production of energy is the goal

1. Boiling water reactors (BWR)
   - Primary coolant ~ 70 atm @ 280 °C (steam)

2. Pressurized Water Reactors (PWR)
   - Primary coolant ~ 150 atm @ 315 °C (liquid)

3. Breeder Reactors
   - Use $^{232}$Th or $^{238}$U as feedstock to produce $^{233}$Th and $^{239}$Pu respectively
   - Produces both energy and fuel
   - Liquid Na coolant, excellent heat conductor
   - Operating in Japan, development in Europe, none operating in US
Current use of Nuclear Power reactors

Number of nuclear reactors (not counting submarines and ships)

- 103 in US
- ~442 in rest of world

Fraction of a nation’s power supplied by nuclear reactors

<table>
<thead>
<tr>
<th>Country</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>20%</td>
</tr>
<tr>
<td>Japan</td>
<td>25%</td>
</tr>
<tr>
<td>Sweden</td>
<td>50%</td>
</tr>
<tr>
<td>Belgium</td>
<td>56%</td>
</tr>
<tr>
<td>France</td>
<td>78%</td>
</tr>
</tbody>
</table>

Has remained at this level for the past 30 years with increased demand despite no new reactor construction.

World-wide, nuclear power plants supply 16% of world energy needs.
Advantage #1: uses indigenous resource

- Lots of U/Th in western US as compared with oil; Geopolitical consequences

Advantage #2: No Chemical Emissions/Oil spills

- no CO₂, CO, O₃, SOₓ, NOₓ
- no particulates
- fewer oil spills (Exxon-Valdez, spill at Golden Gate last week)
Advantage #3 : Efficient land usage

• Coal mining (strip) effectively level mountains
• Wind farms to produce 150 MW uses an area of 7 mi x 5 mi
• Destruction of land for hydroelectric

Crawford County, Photos Courtesy of Kansas Geological Survey

Gob piles

Three Gorges dam, China
Advantage #4: Limited Radiation Emission

Coal fired power plants release on average ten times more radiation due to the Th and U content in coal.

Advantage #5: Safety

Safety record of US, EEC, and Japan is superior to any other source of electrical power; USSR/Russia not so good.

Reason: very tight regulation in the industry.

Advantage #6: Cost

Location dependent – issue is proximity to hydroelectric, coal deposits, solar. Nuclear – cost is up front; fossil fuels pay as you go.

Average production costs—O&M plus fuel—in 1998:
- Nuclear: 2.13 cents/kWh
- Coal: 2.07 cents/kWh
- Natural gas: 3.30 cents/kWh
- Oil: 3.24 cents/kWh.
Disadvantage #1: Personnel exposure to radiation

Workers may receive up to 5 r/yr
- dangers of low levels of exposure are uncertain
- underground coal miners and pilots/flight attendants have higher annual exposure

Disadvantage #2: Radioactivity release

$^3$H, $^{85}$Kr, $^{135}$Xe gases ($\beta$- emitters)

Small with respect to coal, natural radioactivity
Disadvantage #3: Potential accidents

a) Loss of coolant: possible venting of fission products to atmosphere

Three Mile Island incident – radiolysis of H$_2$O is an explosion hazard (not nuclear problem)

b) Core meltdown: expensive, worker exposure (TMI)

Chernobyl – worst documented nuclear accident; design flaw; not adequate containment shield; operated irresponsibly were testing effects of withdrawing control rods and reducing coolant simultaneously; T reached $\sim$2000 °C

Casualties – 36 dead; 200 hospitalized; expect 1500 ± 500 subjected to increased cancer risk; 200 mi$^2$ contaminated
Disadvantage #4: Theft of fissionable material

- especially in former USSR, Third world countries

Disadvantage #5: Storage and Transportation of Nuclear waste

Short term storage – above ground cooling ponds (\(~ 800 \, ^\circ C\))

Transportation after cooling

Long term storage: Not In MY Backyard (NIMBY) syndrome

National Repository (Yucca Mountain) – predict the geologic stability for > 100,000 years
Every 18 to 48 months, nuclear power plants must shut down to remove and replace the "spent" uranium fuel. This spent fuel still contains 90% of its energy content but because of the fission products ("neutron sponges") of the fission process it has become radioactive waste.

All of the nuclear power plants in the United States together produce about 2,000 metric tons per year of radioactive waste. Currently, the radioactive waste is stored at the nuclear plants at which it is generated, either in steel-lined, concrete vaults filled with water or in above-ground steel or steel-reinforced concrete containers with steel inner canisters. In addition to the fuel waste, much of the equipment in the nuclear power plants becomes contaminated with radiation and will become radioactive waste after the plant is closed. These wastes will remain radioactive for many thousands of years.
Operating nuclear power reactors

http://www.nrc.gov/info-finder/reactor/
Sites storing spent nuclear fuel, high level radioactive waste and/or surplus plutonium.

http://www.ocrwm.doe.gov/
The Department of Energy’s Office of Civilian Radioactive Waste Management is using a “multiple” barrier approach to isolate the waste. This approach addresses the primary safety issues of:

• preventing water from reaching the waste canisters,
• dissolving the canisters and waste, and
• carrying radioactive particles away from the repository.

Yucca Mountain, Nevada – A national repository

• 1000 feet below the earth’s surface
• 1000 feet above the water table
Transport of Nuclear Waste

http://www.ocrwm.doe.gov/exhibits/trans5a.swf
Solution: Reprocessing of spent nuclear fuel

“Spent” fuel contains a significant amount of unused $^{235}\text{U}$ (95% of energy)

Separate short lived waste from long-lived waste

---

Report to Congress
on
Advanced Fuel Cycle Initiative: The Future Path for Advanced
Spent Fuel Treatment and
Transmutation Research

![Graph: Constituents of Spent Nuclear Fuel]

**Figure II-1:** Spent fuel is nearly 96 percent uranium—simply removing this material would result in a dramatic reduction in the volume of nuclear waste.
Nuclear processing is not a new idea

La Hague built in 1976 treats 1650 tons of spent fuel a year
Facility to process 800 tons/year nearly ready to open in Japan

Reprocessing, as done by the French, does not reduce the amount of high-level waste.
Following the detonation by India of a nuclear bomb in 1974 made from plutonium reprocessed from a civilian reactor waste President Carter banned re-processing of US nuclear waste.

President Ronald Regan revoked Carter’s ban but the US continued to steer clear of reprocessing due to its cost/cheap supply of uranium.

This led to the use of the “one time through” policy in the US.
Goals of AFCI

1) **Reduce Spent Fuel Volume** by creating a final high-level waste form that is lower in volume than the original spent fuel,

2) **Separate Long-Lived, Highly Toxic Elements** (*i.e.*, actinides such as plutonium and americium) that present the most difficult disposition challenge, and

3) **Reclaim Spent Fuel’s Valuable Energy** by providing a method to reclaim the energy value contained in the highly toxic spent fuel elements while providing for their destruction.
Transmuting long-lived radioactive products

**WHAT IS TRANSMUTATION?**

**Transmutation** refers to the ability to transform one atom into another by changing its nuclear structure. This is accomplished by bombarding the atoms of interest with neutrons either in an accelerator or a nuclear reactor. In the context of spent nuclear fuel, transmutation can convert plutonium and other actinides into isotopes with more favorable characteristics.

**Neutron Capture**

- **Neutron**
- **I-129**
- **I-130**
- **Xe-130**
- **Non-Radioactive**

**Beta Particle**
Transmuting the long-lived radioactive products:

a) Lowers the toxicity of the stored waste

b) Reduces the heat load on the repository

c) Reduces the need to guarantee the geologic stability of the observatory for an extremely long time scale.

Figure III-1: Advanced spent fuel treatment and transmutation can lead to large reductions in the long-term radiotoxicity of materials contained in a geologic repository.
Global Nuclear Energy Partnership (GNEP)

Development of UREX and UREX+ extraction methods at Argonne National Laboratory represent a real advance in handling of spent reactor fuel. Presently at pilot stage, commercial facility probably within a decade.
Summary

1. Nuclear power is a well established means or reliably and safely providing power on a scale that is needed. (Medium term solution of 50-100 years.)

2. It does not contribute greenhouse gases to the atmosphere and thus is an integral part of meeting increasing global energy needs.

3. Dealing with the storage and recycling of “spent” nuclear fuel is an important issue, but recent advances such as UREX show it is a solvable problem.