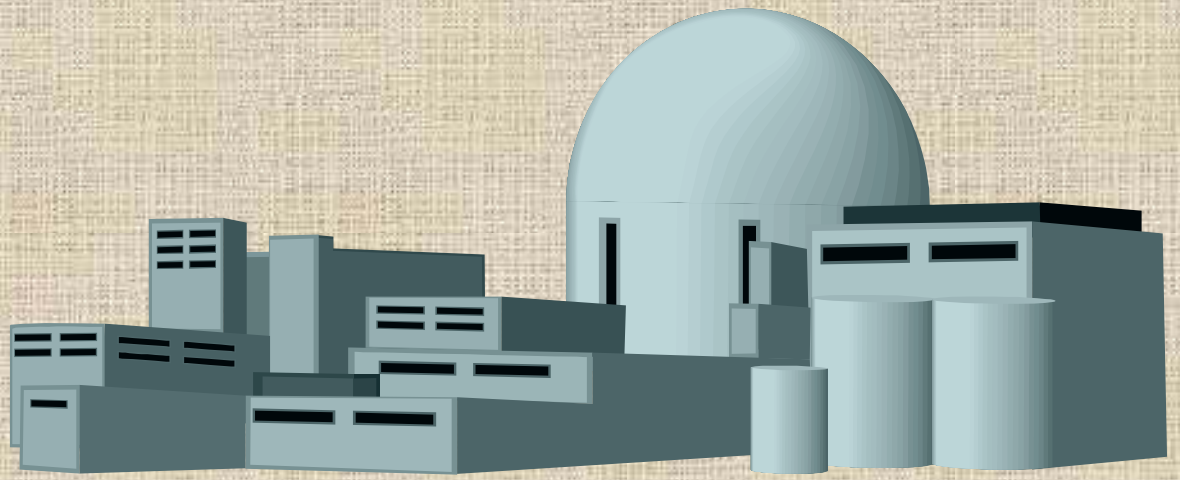
Nuclear Energy

A clean, renewable power source with a troubled past and an uncertain future

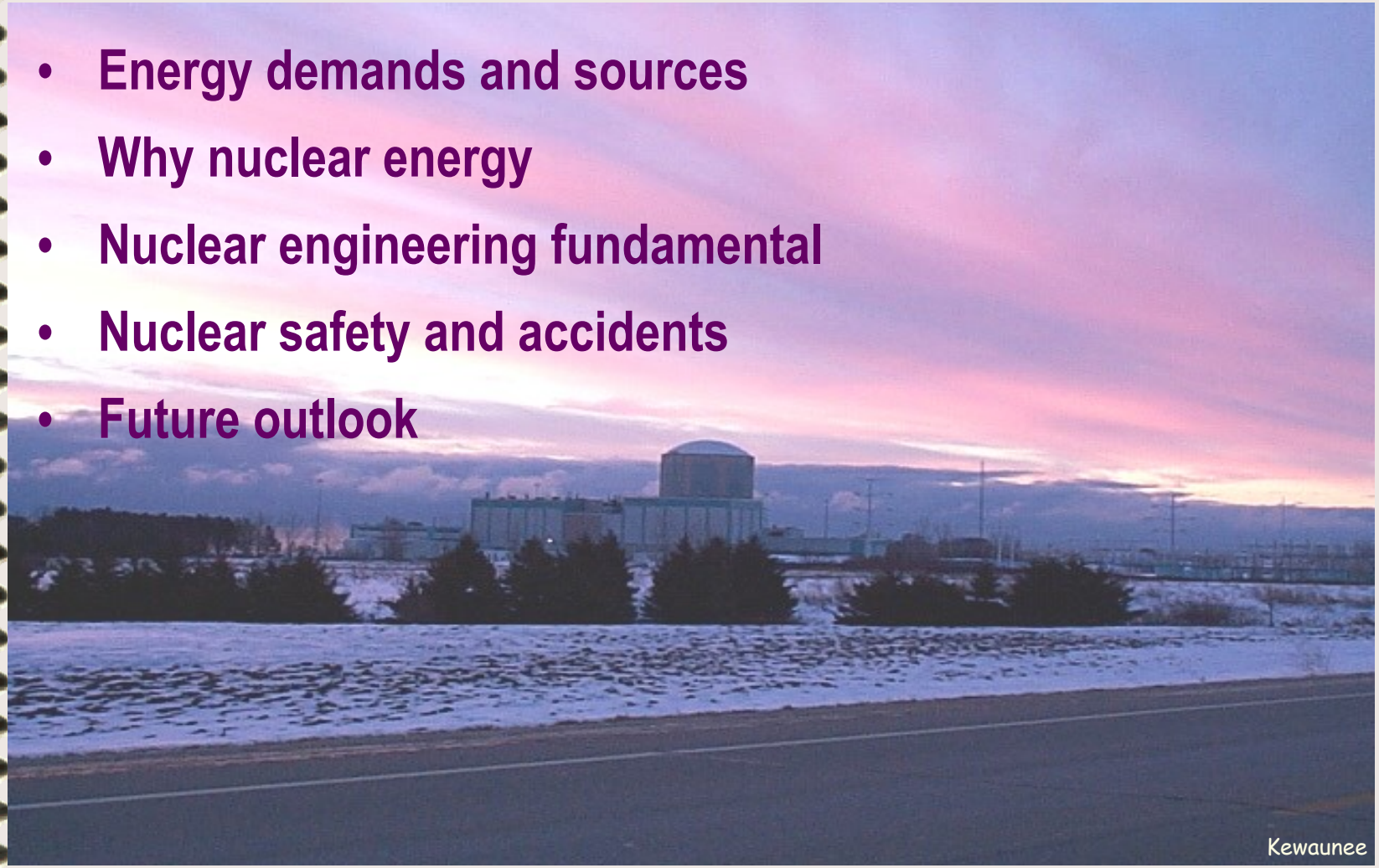


Vincent Ho

18 June 2009

Topics to cover

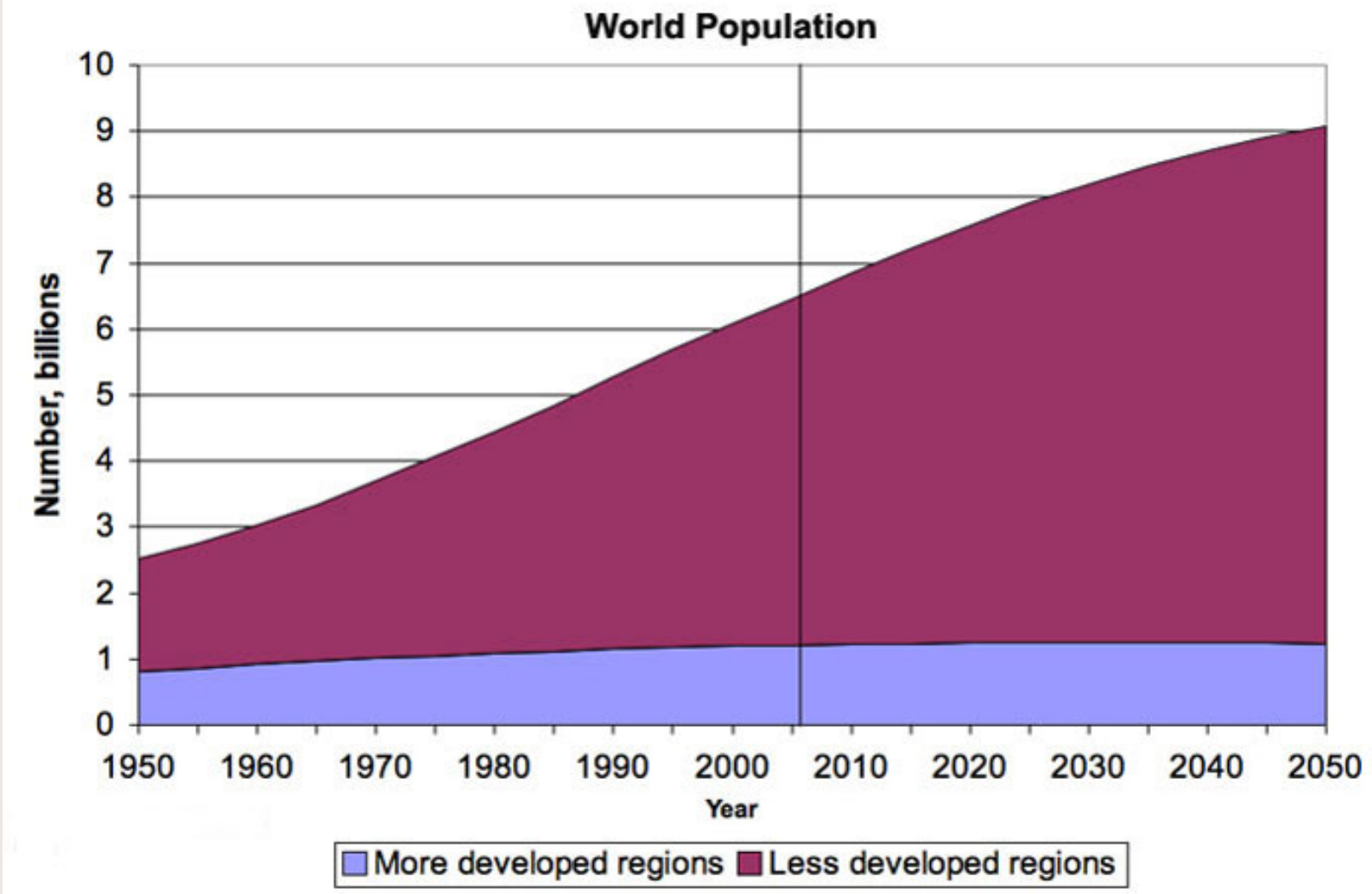
- Energy demands and sources
- Why nuclear energy
- Nuclear engineering fundamental
- Nuclear safety and accidents
- Future outlook



We use a lot of energy…

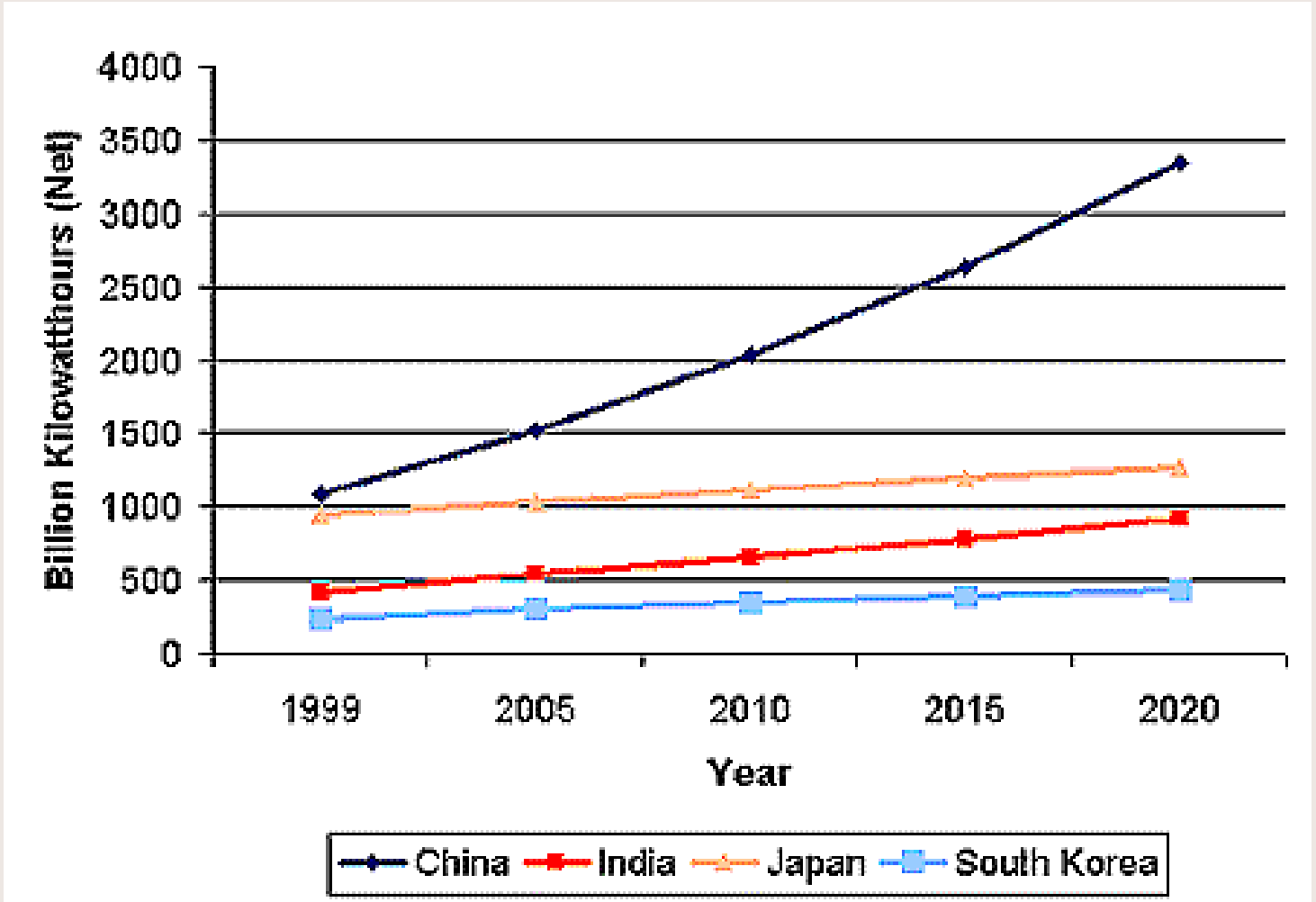
and we will use more and more…

Not only we use more energy-dependent gadget per capita, the world is growing



World energy consumption is always on the rise

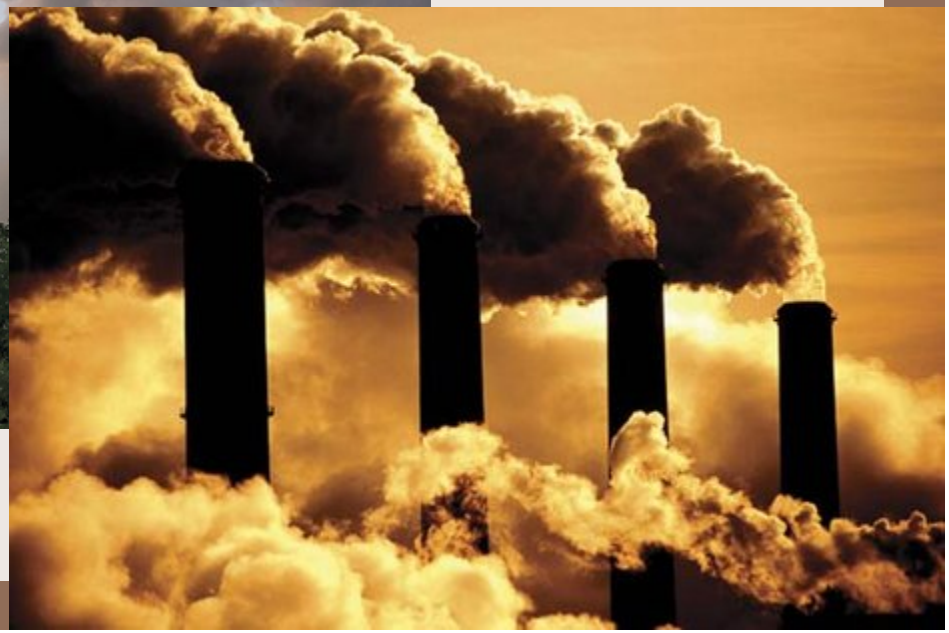
Demand in China is expected to grow at a faster rate than our neighbors



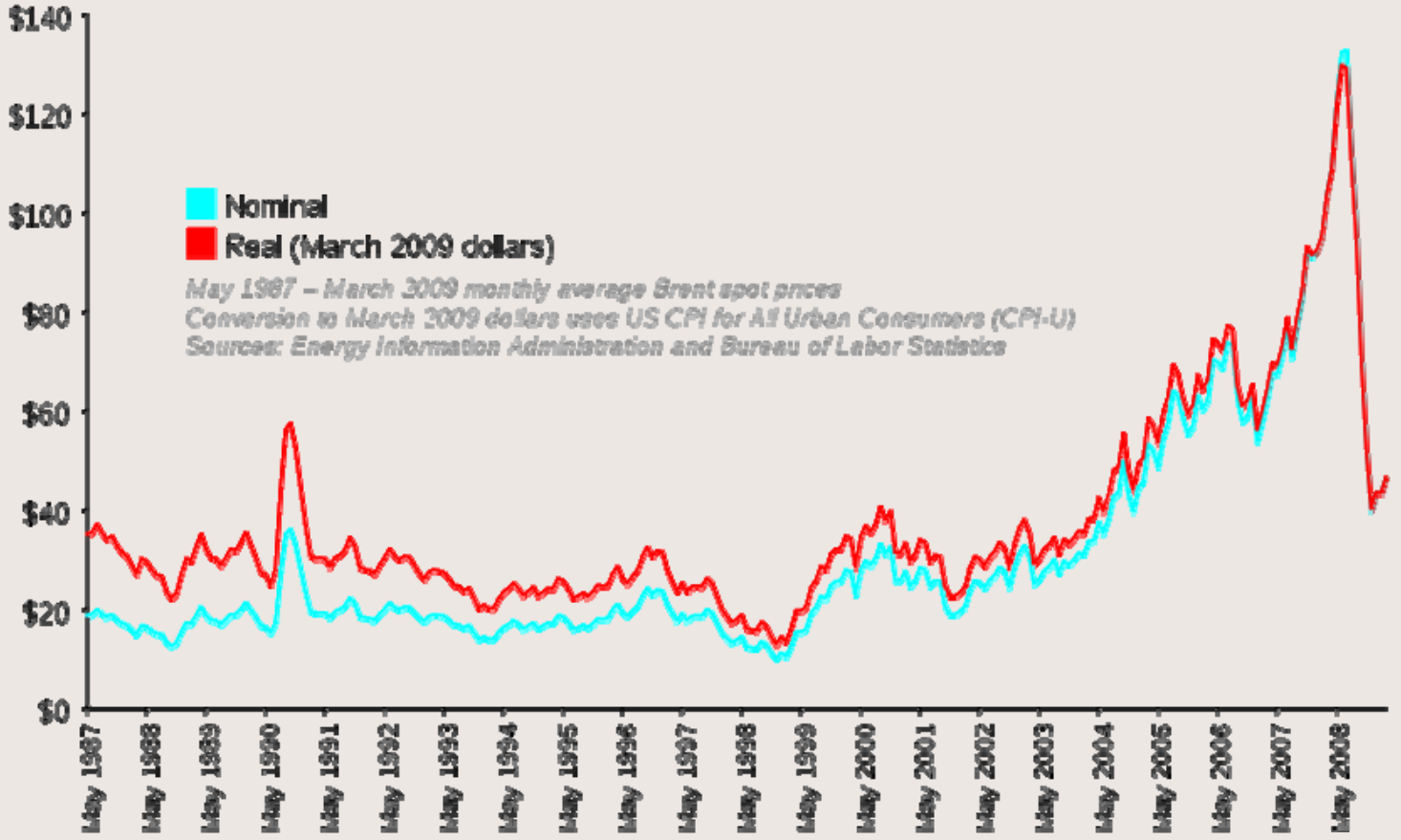
Thermal power plants using fossil fuels is the primary energy source in china

By the way, we don't really "produce" energy, we "harvest" or "transform" them

Fossil fuel can be very dirty

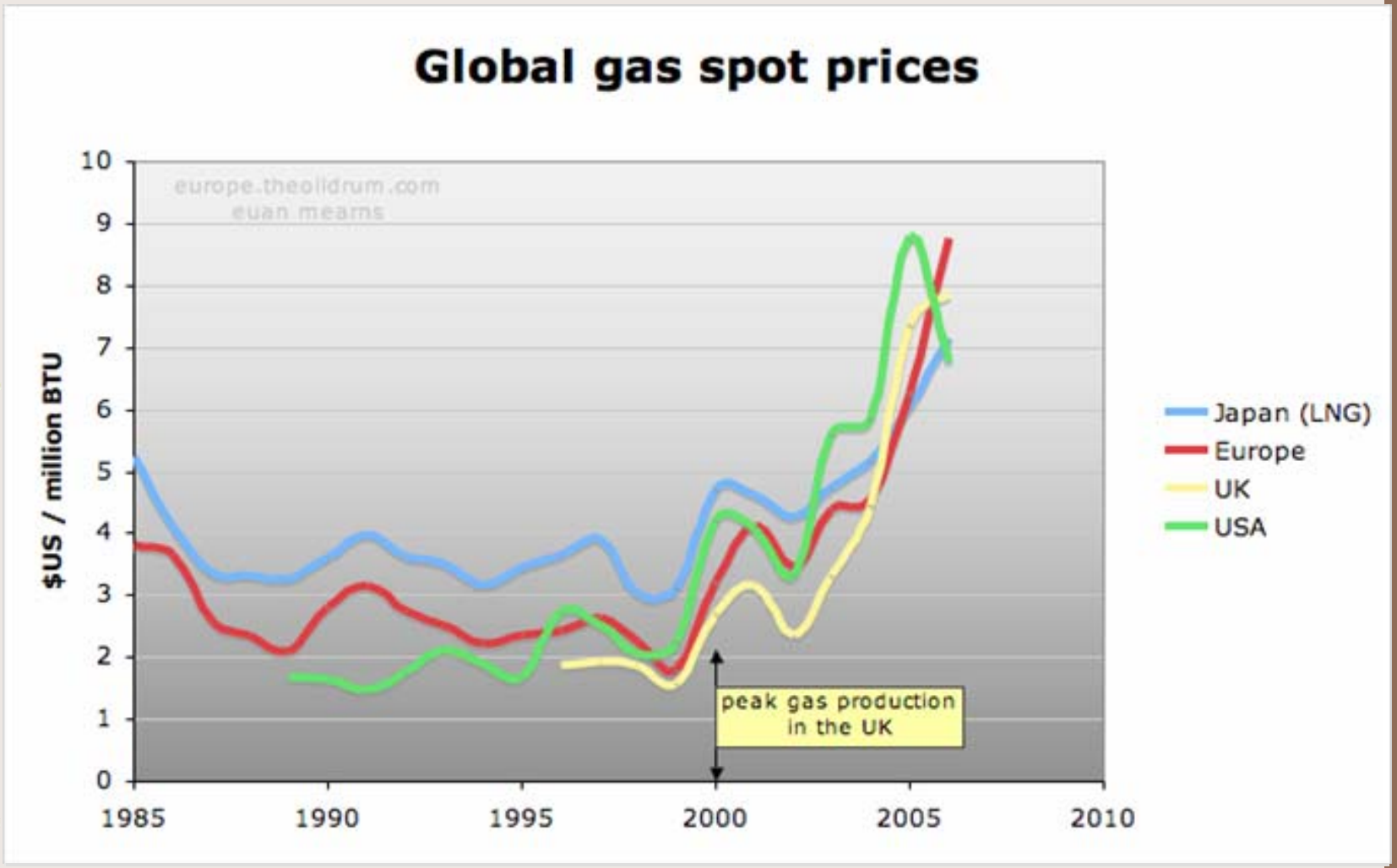


Oil price can go up, WAY UP, and it did

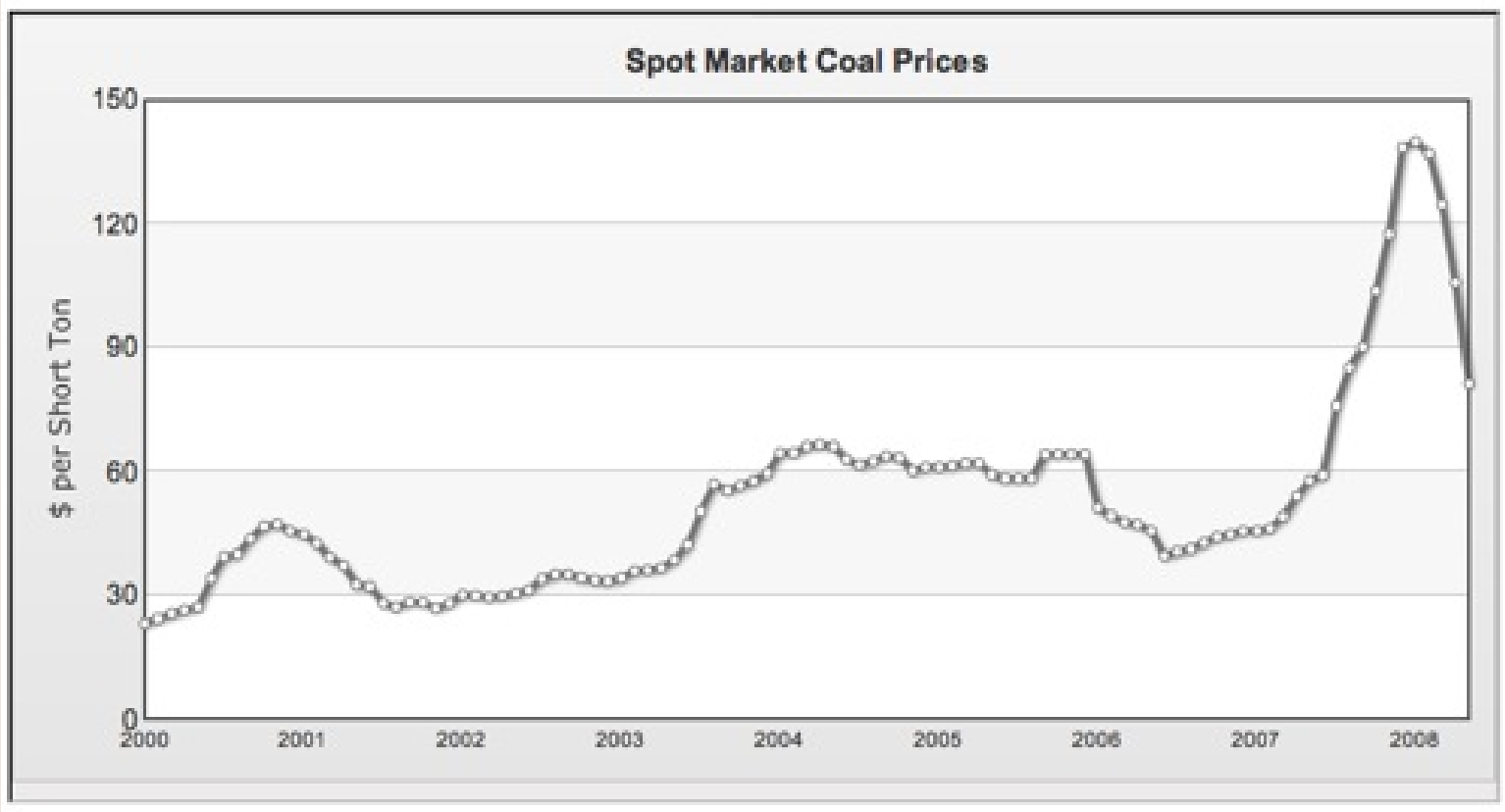


XXX predicts oil price of $200 a barrel in next 2 years…

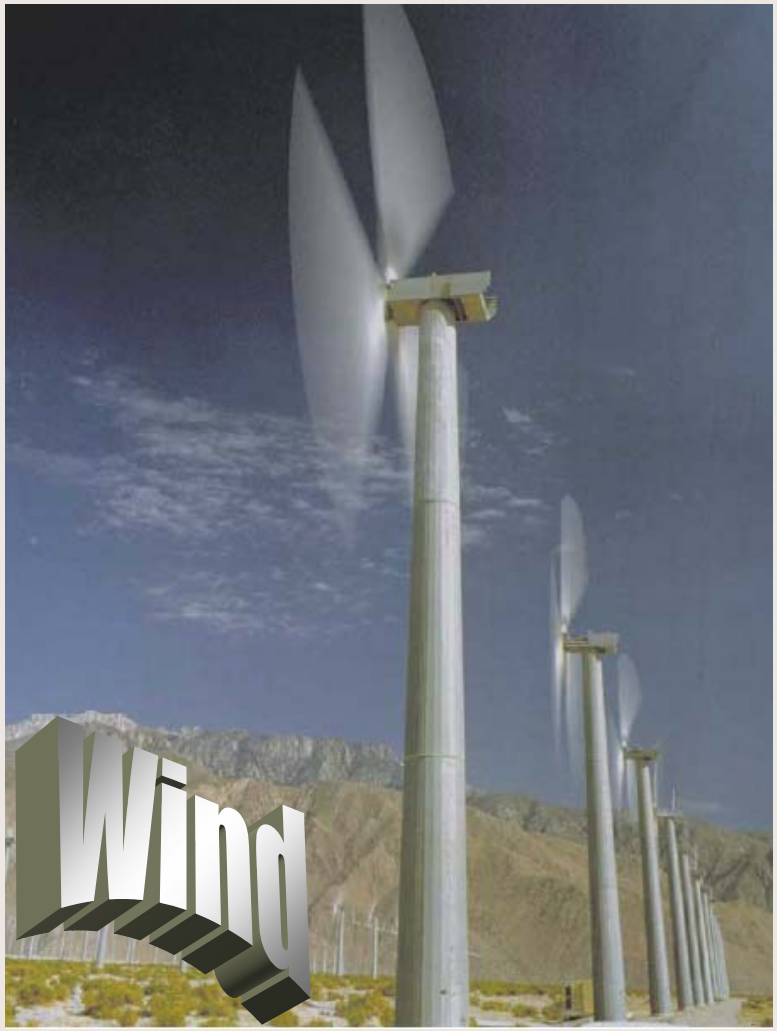
Natural gas price has also gone up steadily, almost unnoticed

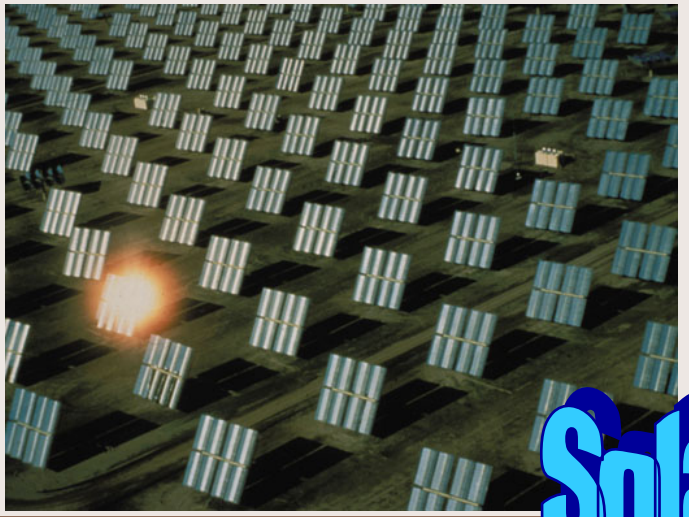


Coal price follows



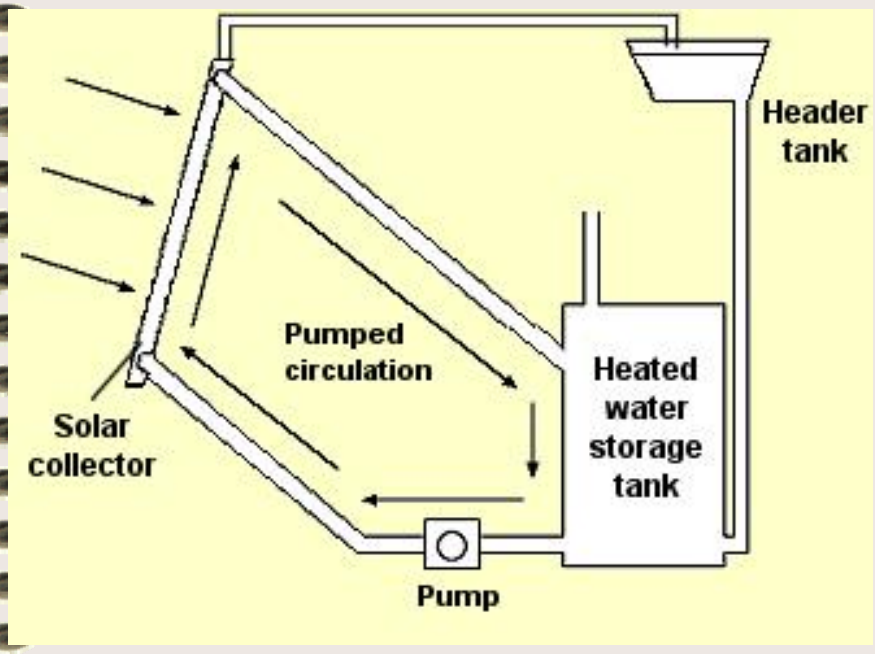
We constantly look for clean, renewable energy sources

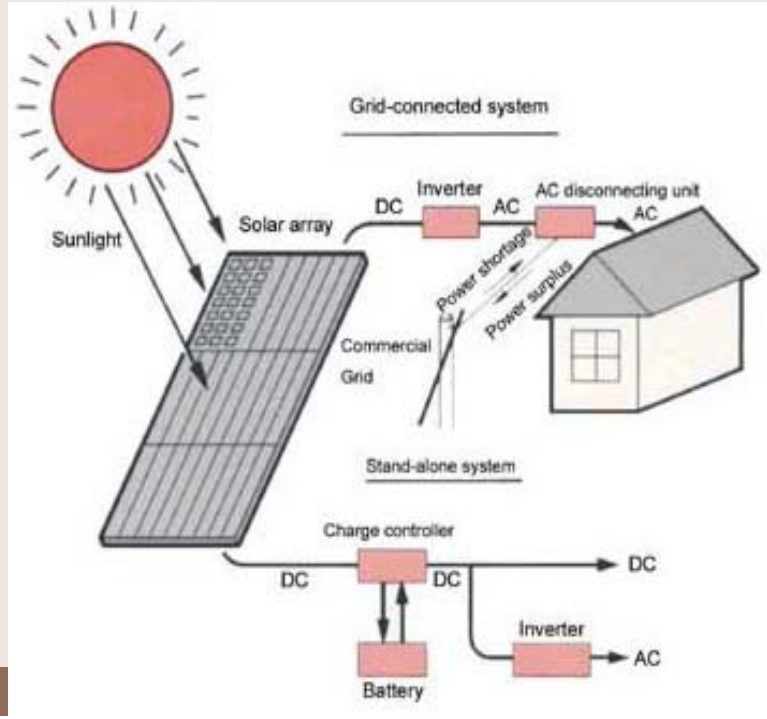




Solar energy – household application

- Solar-thermal methods utilize panels or “collectors” that heat a fluid, which is in turn used for heating (thermal) or for generating electricity (power)
- Solar energy often used now to heat household water





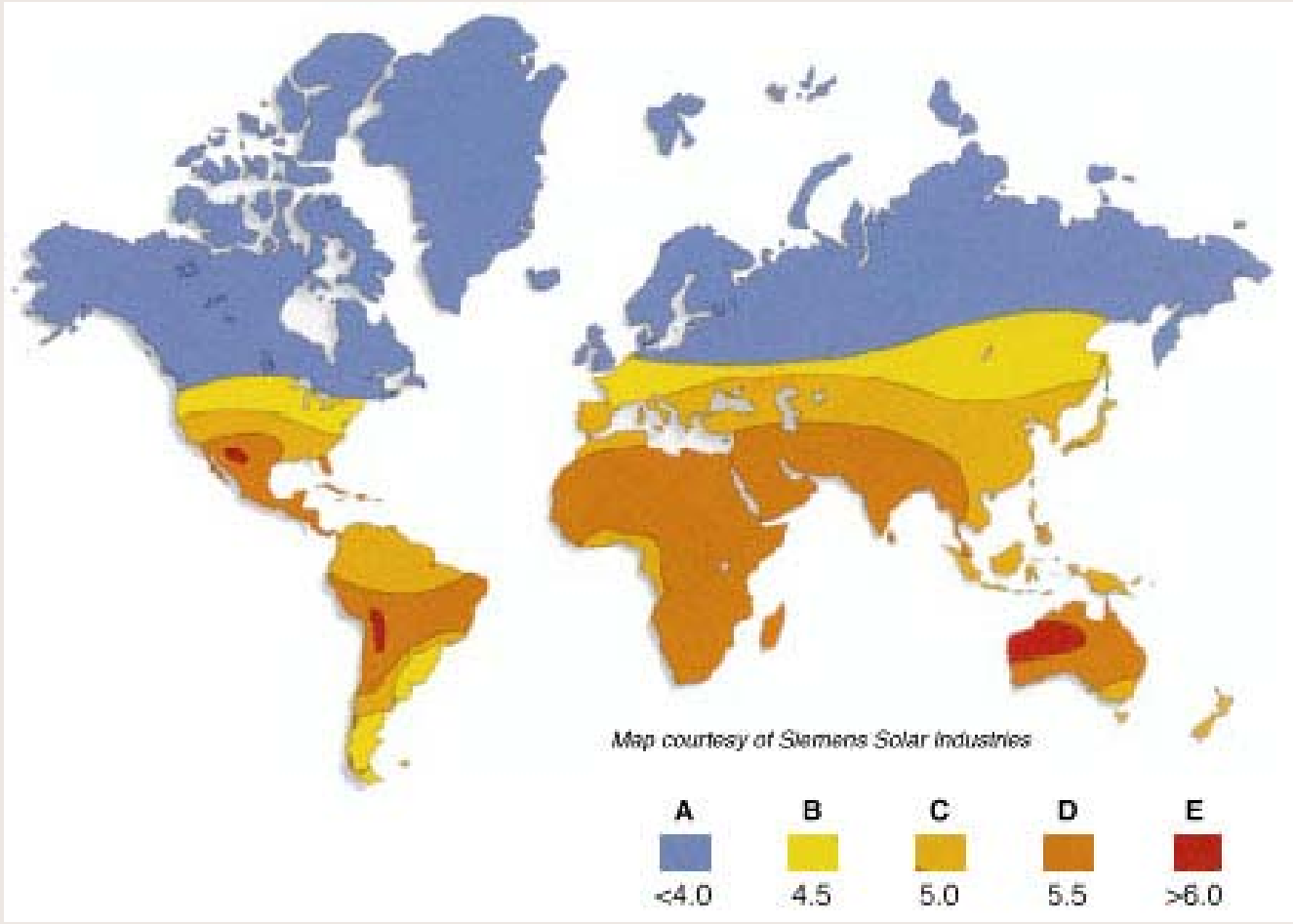
Solar panels to heat water (or other medium)

- Photovoltaic cells use the second most common element on earth, silicon, to convert light directly into electricity (direct conversion)
- Costs need to fall another 50-70 percent to make solar energy competitive

Solar energy – larger scale production

- Solar energy station in Mojave Desert near Barstow
  - Receivers capture light energy which heats water
  - Super heated water then transferred to plant where it flashes to steam to drive turbines that operate electrical generator

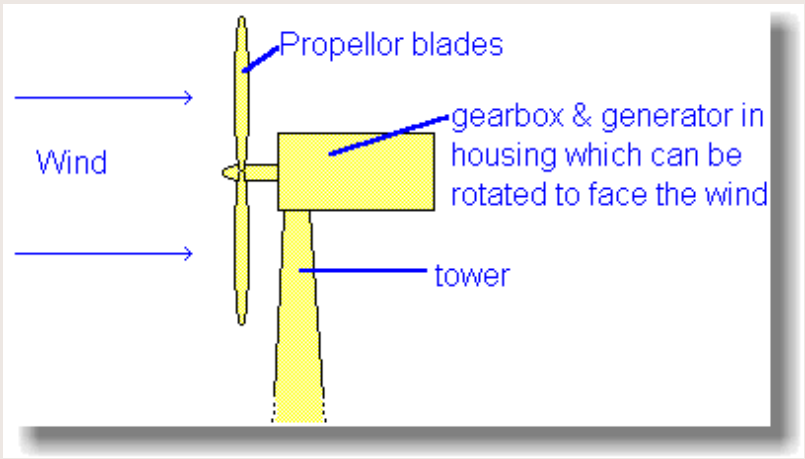
Average hours of sunshine



…what are the other disadvantages of solar power?

Wind energy - how does it work?

- **Wind velocity turns large turbines that in turn generate electricity**



Wind energy

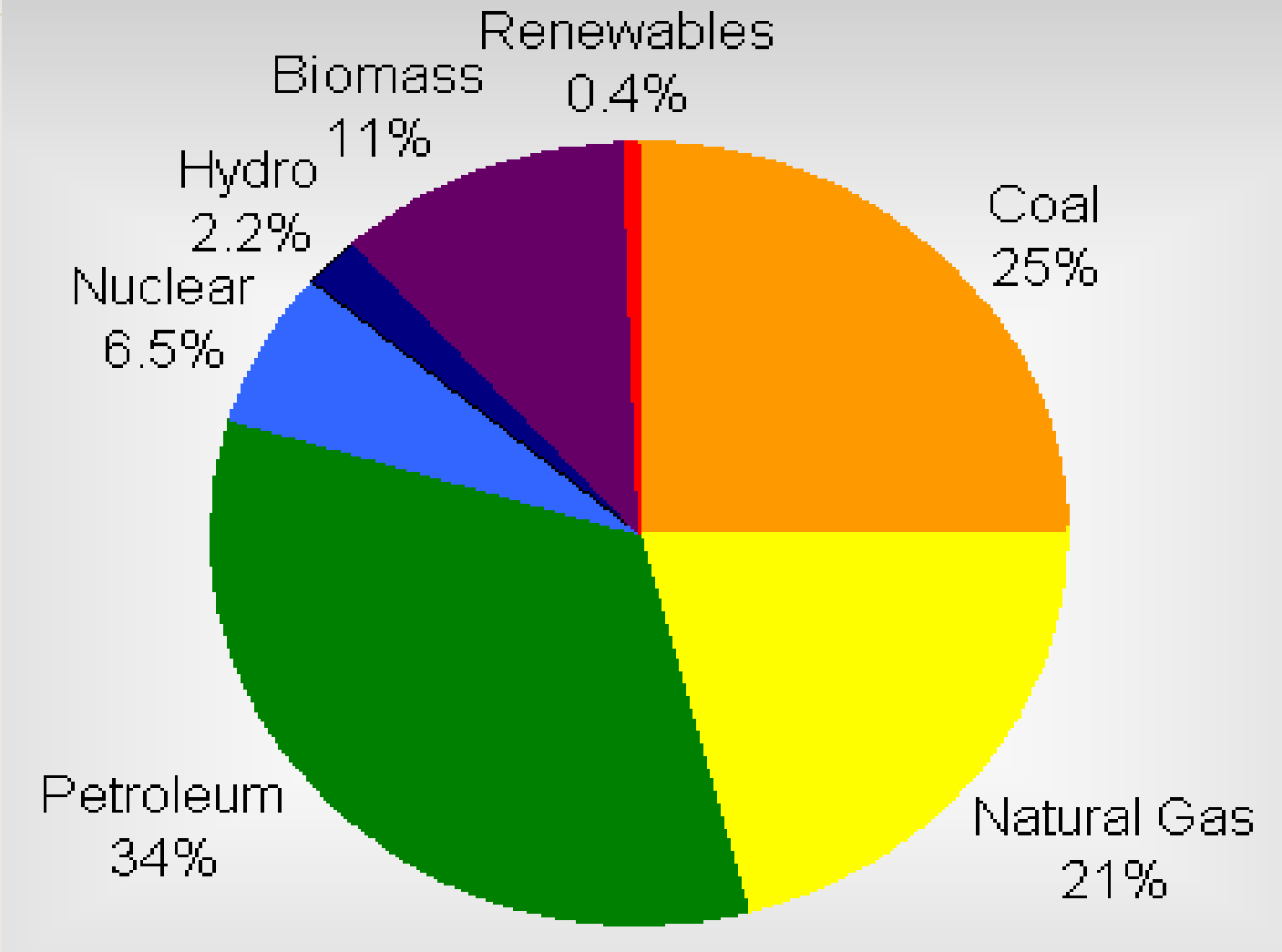
- Fastest growing energy segment in the world and has been for 25 years
- Cost of wind power has dropped by 90%.
- In 20 years, wind energy will be a top competitor for energy provision

…what are the disadvantages of wind power?

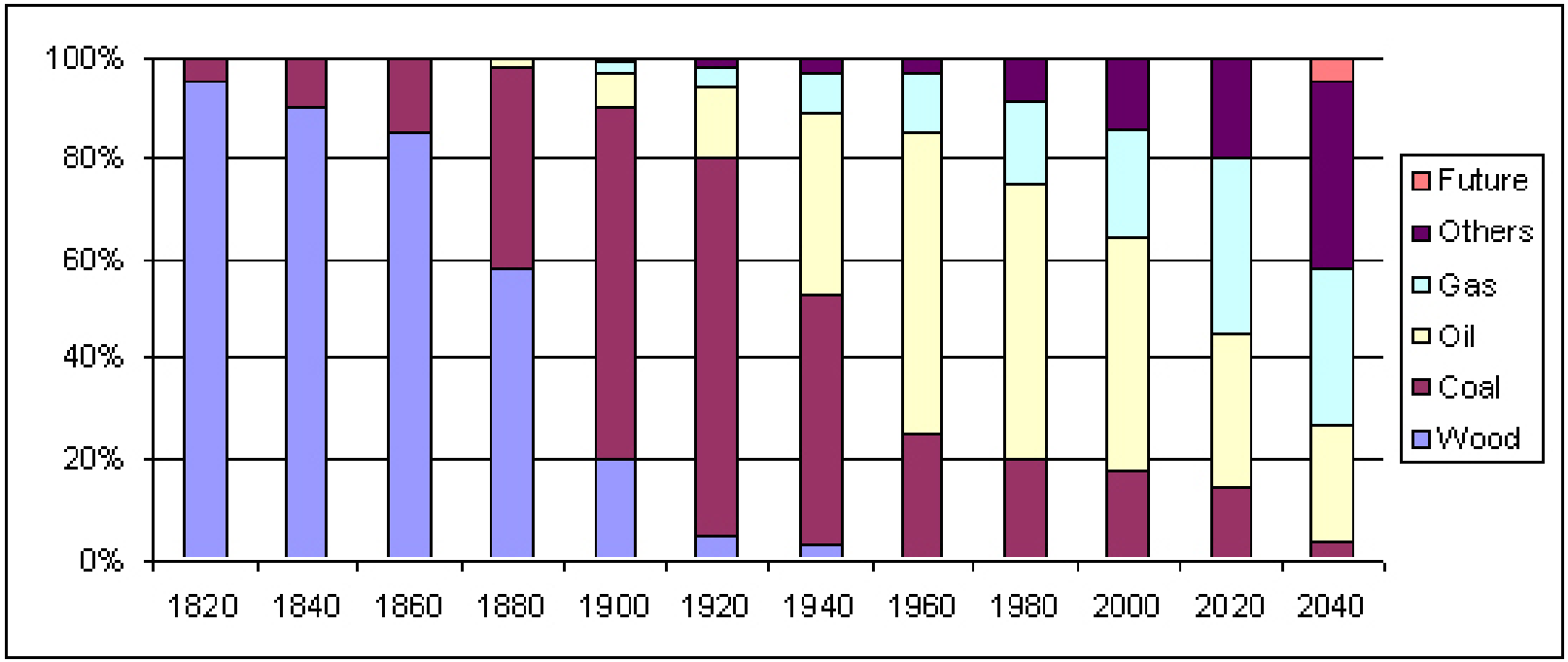
Other alternate renewable energy sources

- Geothermal energy
  - Deep heat from earth rises to shallower depths, heat drives steam-turbine generators. Good outlook for future production
- Ocean Thermal Energy Conversion
  - Utilizes temperature differences between warm surface water and colder deep waters to vaporize a low-boiling fluid and operate a generator
- Wave Energy
  - Still impractical, idea of using wave power to turn turbines
- Tidal Currents
  - Utilize basins that fill with seawater at high tide and empty at low tide, generating electricity in the process

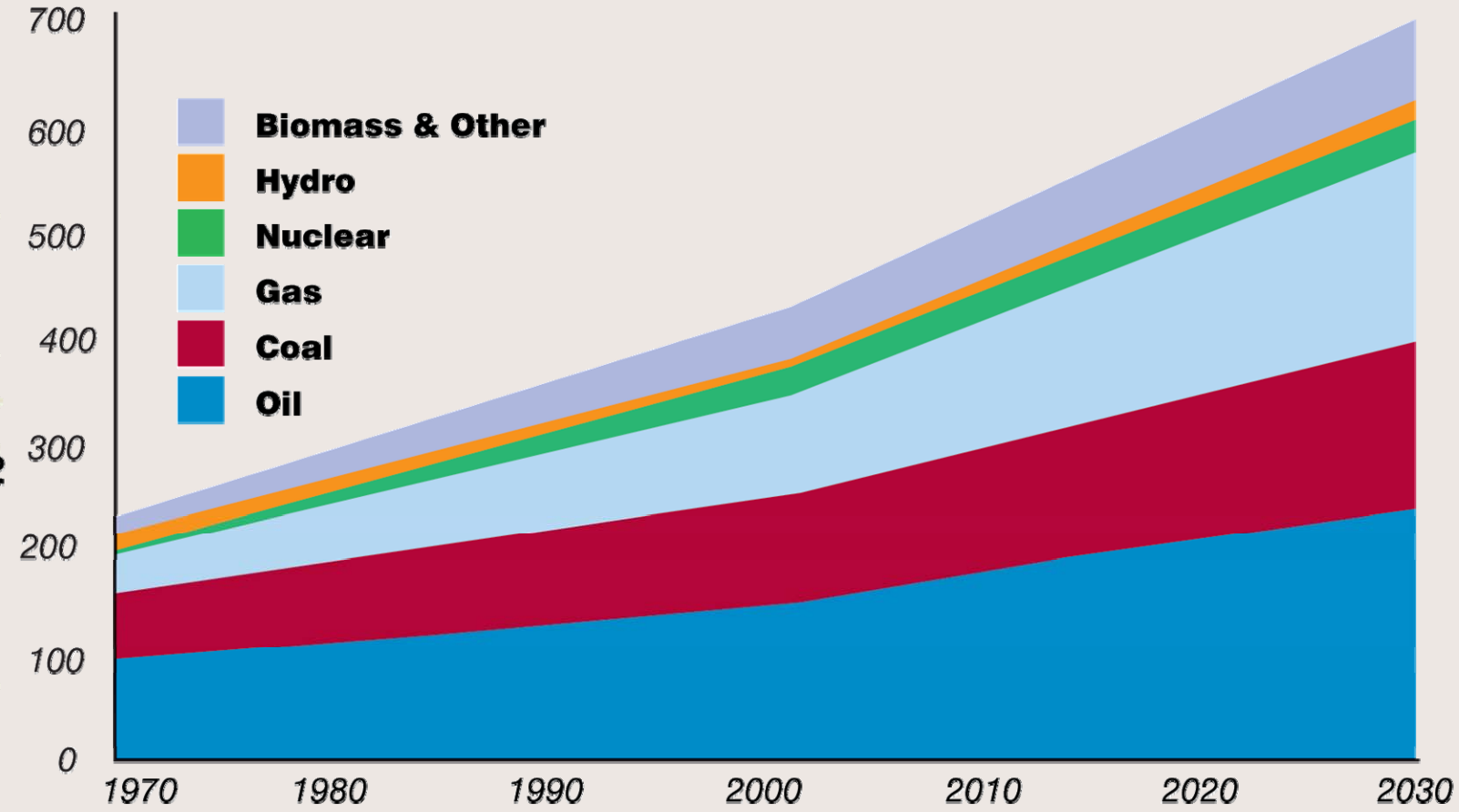
World energy production… a snap shot at 2006



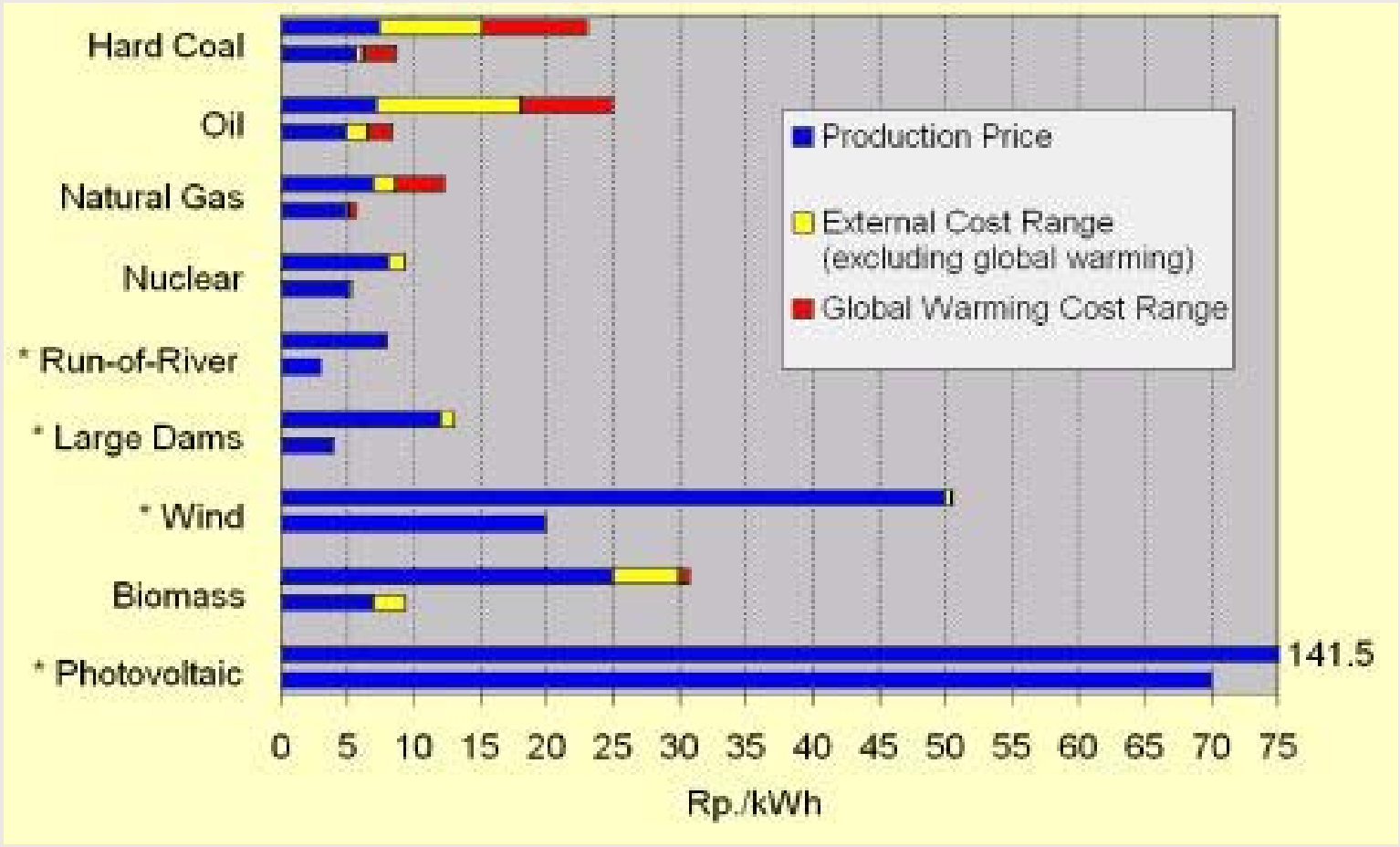
Shift of energy source dependence in USA



Shift of world energy source dependence

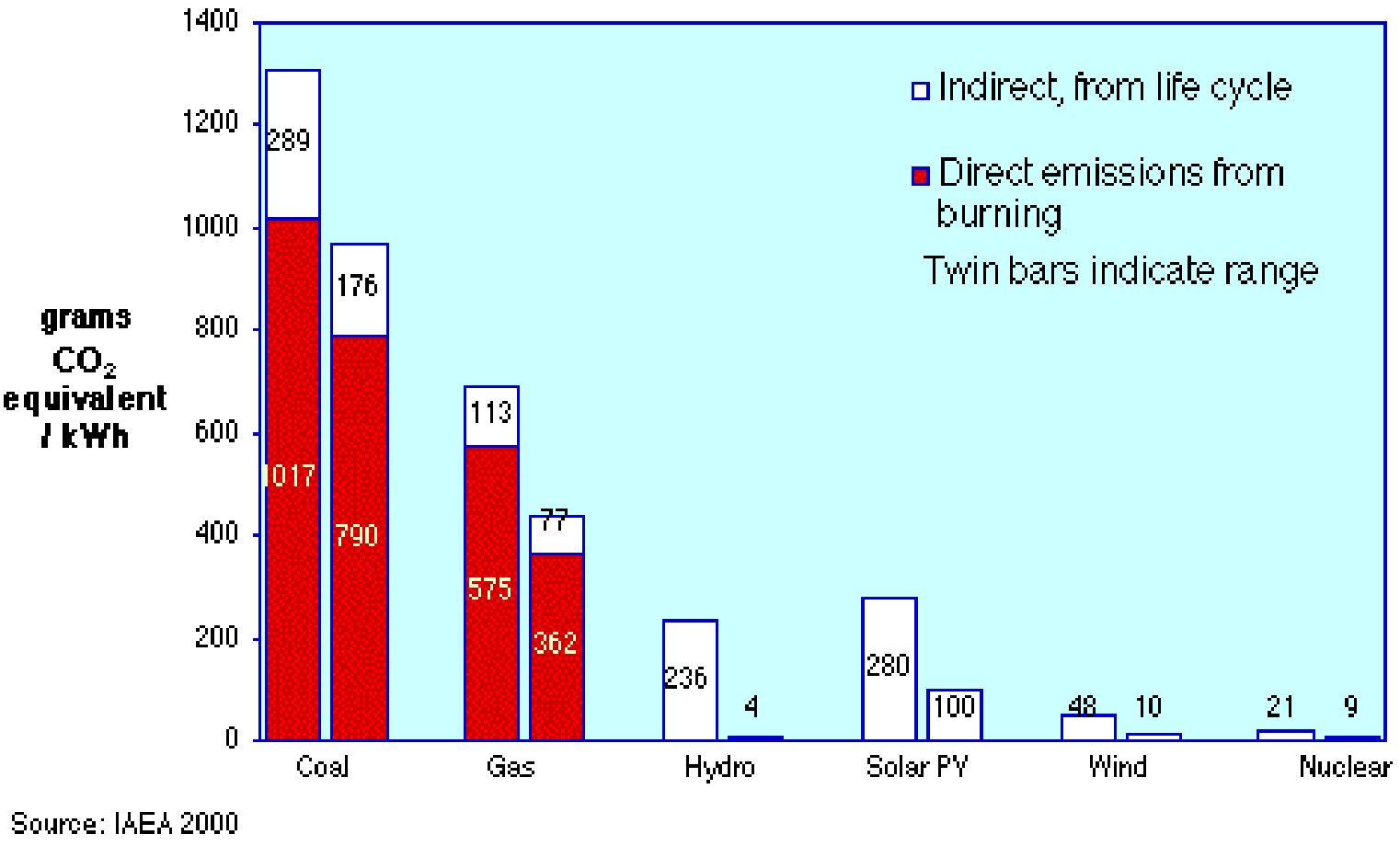


The high production cost of renewable energy slows down its growth



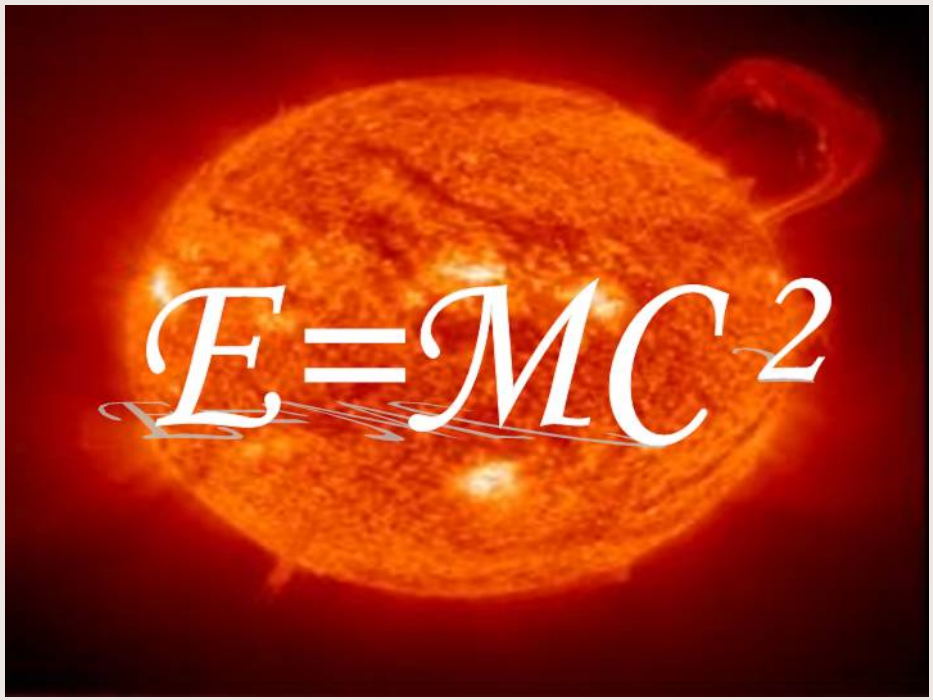
Rp = cents SFR)

Greenhouse gas emission from electricity production



Source: IAEA 2000

One clean energy source was discovered through physics calculation

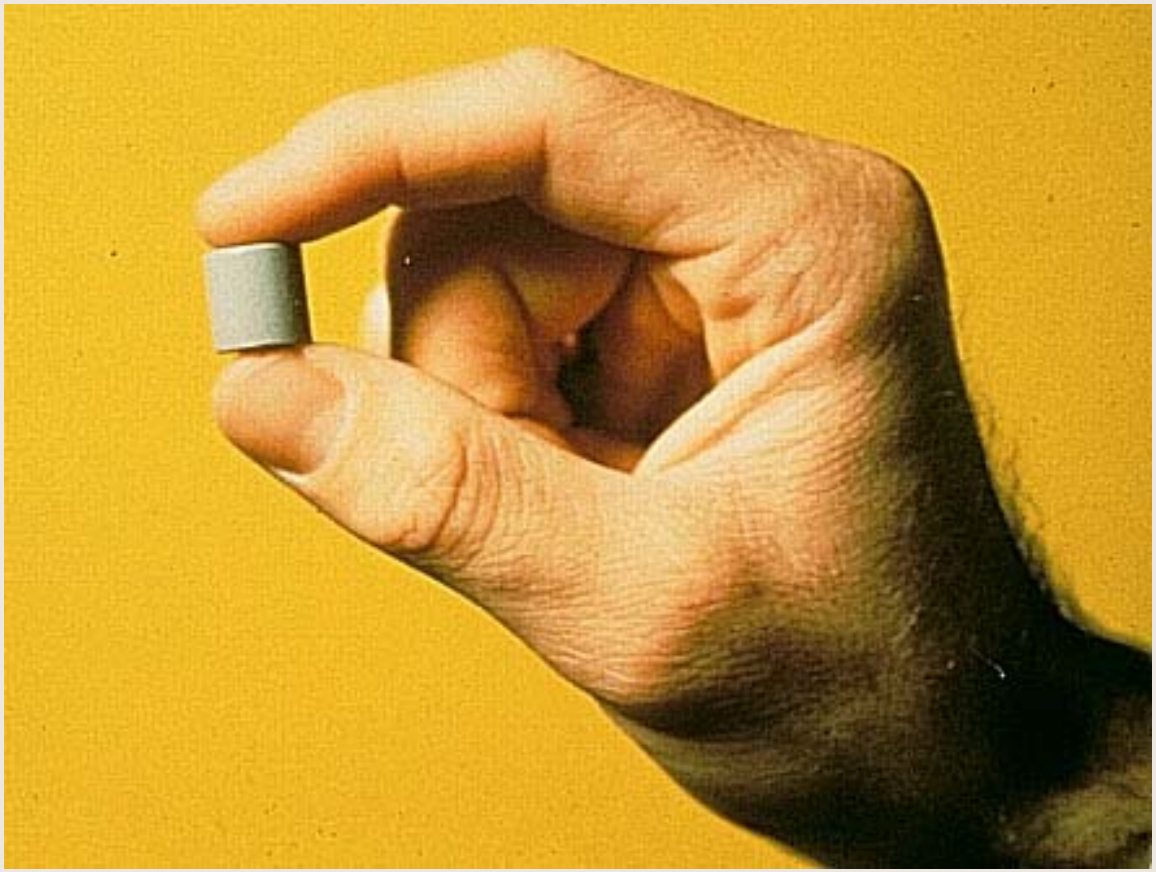


NUCLEAR ENERGY!!

Nuclear energy was first used as a weapon of mass destruction

Nuclear energy has been considered a “bad” thing for its destructive capability

How do we harvest energy safely for our use from such a small nuclear fuel pellet?



…by the application of nuclear engineering

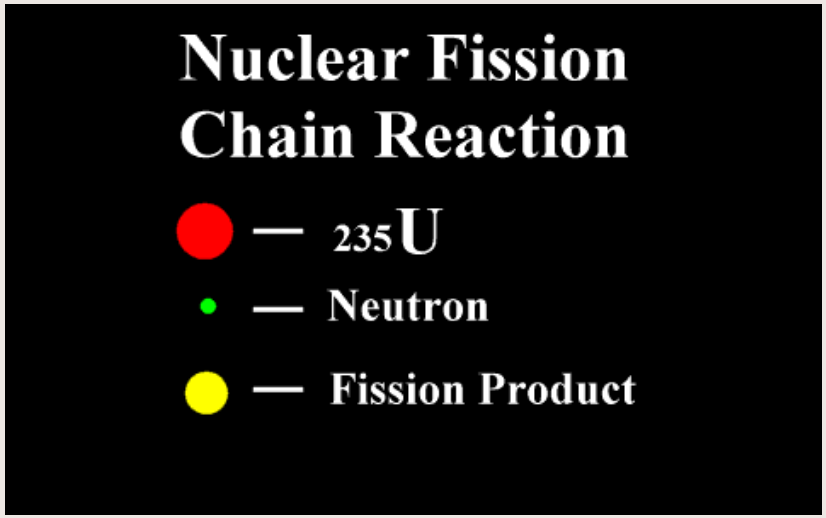
Nuclear fission – splitting atoms to extract energy

- Energy is released when atom is split, $E = MC^2$
- Uranium and Plutonium are typical fuel for reactors and weapons

$$^{235}U + \text{neutron} \rightarrow \text{fission fragments} + 2.4 \text{ neutrons} + 192.9 \text{ MeV}$$

Chain reaction

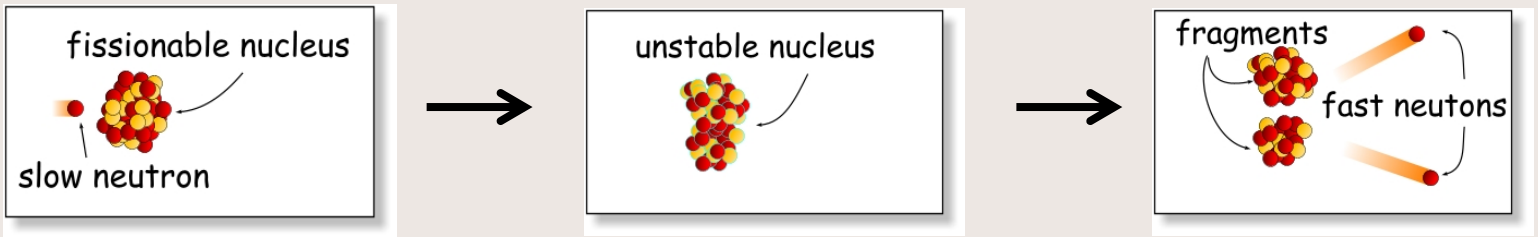
- Each fission can create 2 to 3 neutrons in every millisecond, causing a chain reaction



- Effective neutron multiplication factor, k, is the average number of neutrons from one fission that cause another fission
  - $k < 1$ sub-critical
  - $k = 1$ critical
  - $k > 1$ super-critical

Nuclear criticality

- Fissile neutrons are fast neutrons and must be slowed down by “Moderators” to ensure a sustained k ≥ 1
- Super-criticality
  - Delayed Critical, k = 1/(1-β), where power reactors operate
  - Prompt Critical, k > 1/(1-β), where nuclear weapons operate
  - β=fraction of delayed neutrons
- Nuclear reactors are designed to control the chain reaction by slowing down and absorbing neutrons, and to transform the released energy into usable form

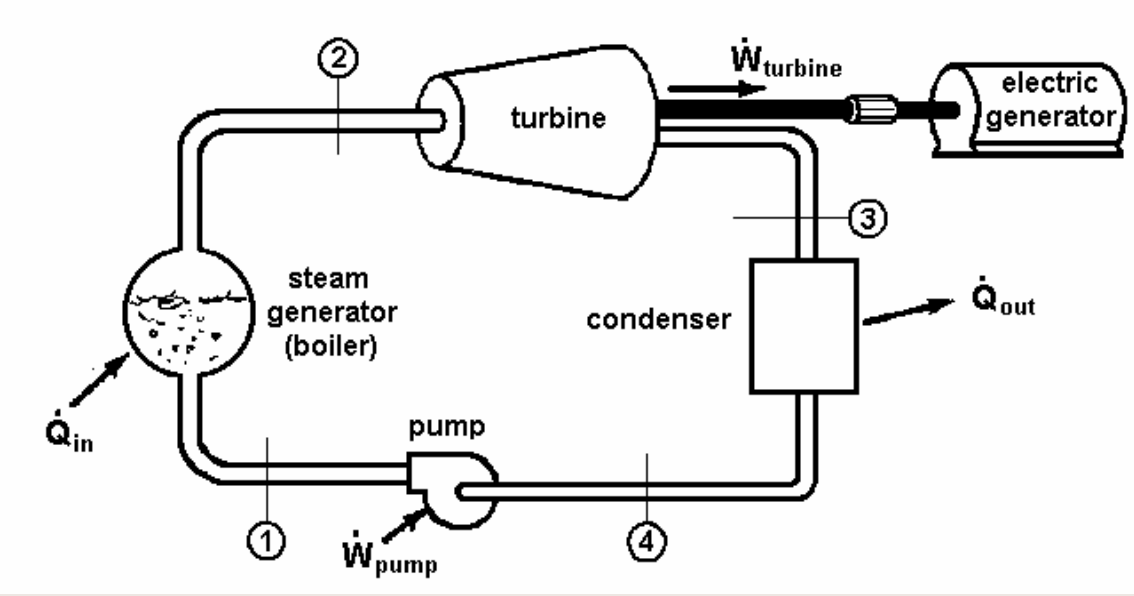


Nuclear power plants

- Reactors cannot blow up like a nuclear weapon; hydrogen explosion is possible
- Many types of nuclear reactor but most commonly used for power generation are:
  - PWR (Pressurized Water Reactors)
  - BWR (Boiler Water Reactors)
- A nuclear power plant (NPP) is basically a steam engine using nuclear fission as heat source
- Some nuclear reactors can even produce more fuels than they were originally given – Breeder Reactor

Power generation – Rankine cycle steam engine

- ① → ② **Water is heated to steam** (isobaric heat supply)
- ② → ③ **Steam is expanded** (isentropic expansion)
- ③ → ④ **Steam is cooled to water** (isobaric heat rejection)
- ④ → ① **Water is pumped to boiler** (isentropic compression)

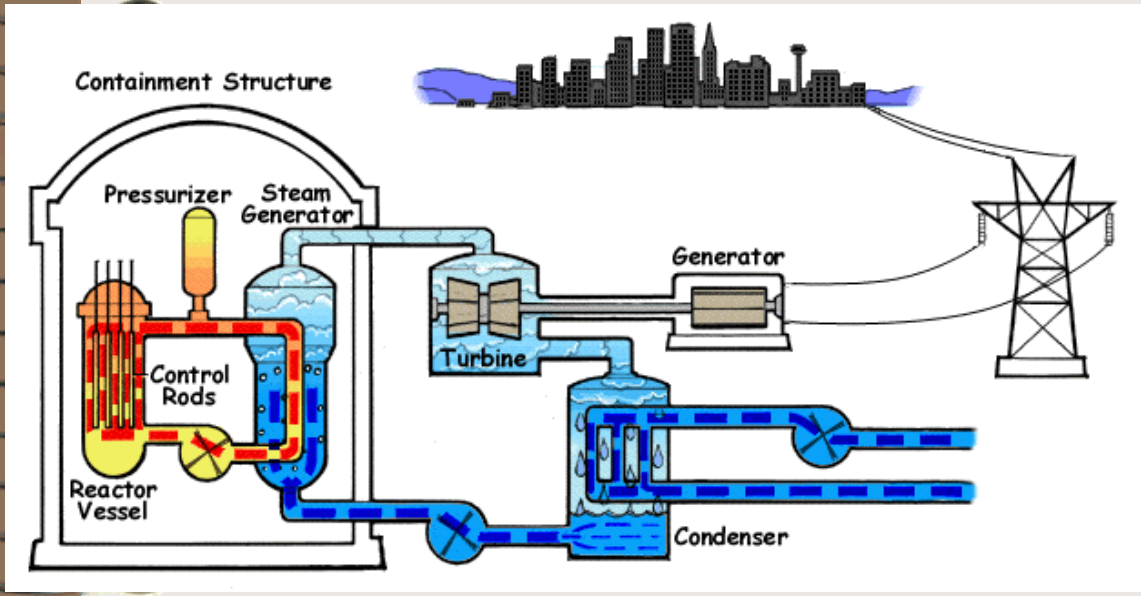


Common types of nuclear reactors

- PWR (Pressurized Water Reactors)
- BWR (Boiler Water Reactors)
- GCR (Gas Cooled Reactors)
- WWER or VVER (Water Water Energetic Reactors)
- RBMK (Graphite Moderated, Boiling Water Cooled Channel Type Reactors)
- CANDU (Canada Deuterium Uranium Reactors)
- LMFBR (Liquid Metal Fast breeder Reactors)

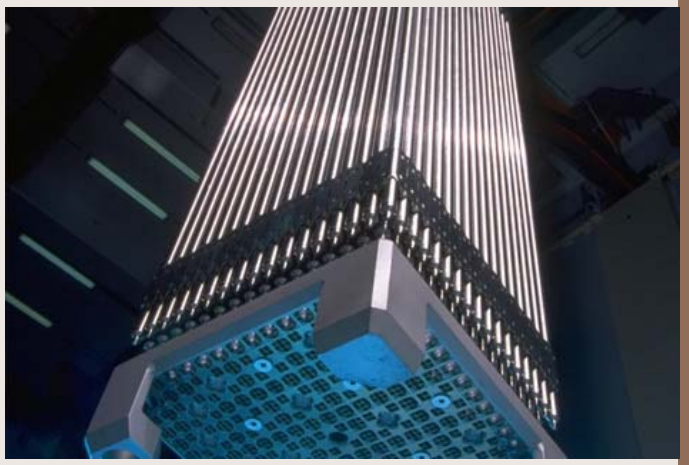
PWR – Pressurized Water Reactors

- Compressed water is heated in a closed primary loop
- The heat is transferred to a non-radioactive secondary loop through steam generators



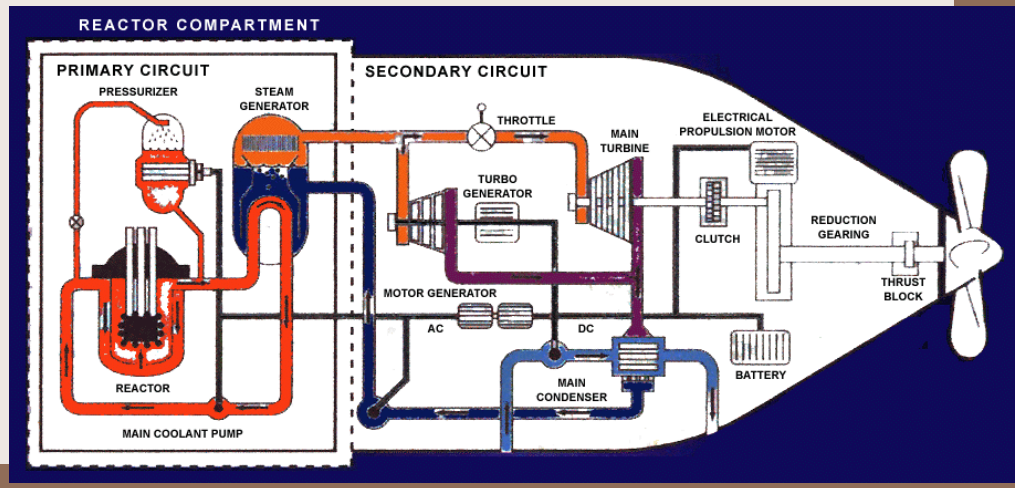
The PWR reactors

- Dominant Technology in the USA
- Effectively an off the shelf design
- Flexible fuelling – French PWRs investigation MOX fuel
- Must take off load to refuel
- Safe operating characteristics – but still possibility of core damage due with loss of coolant



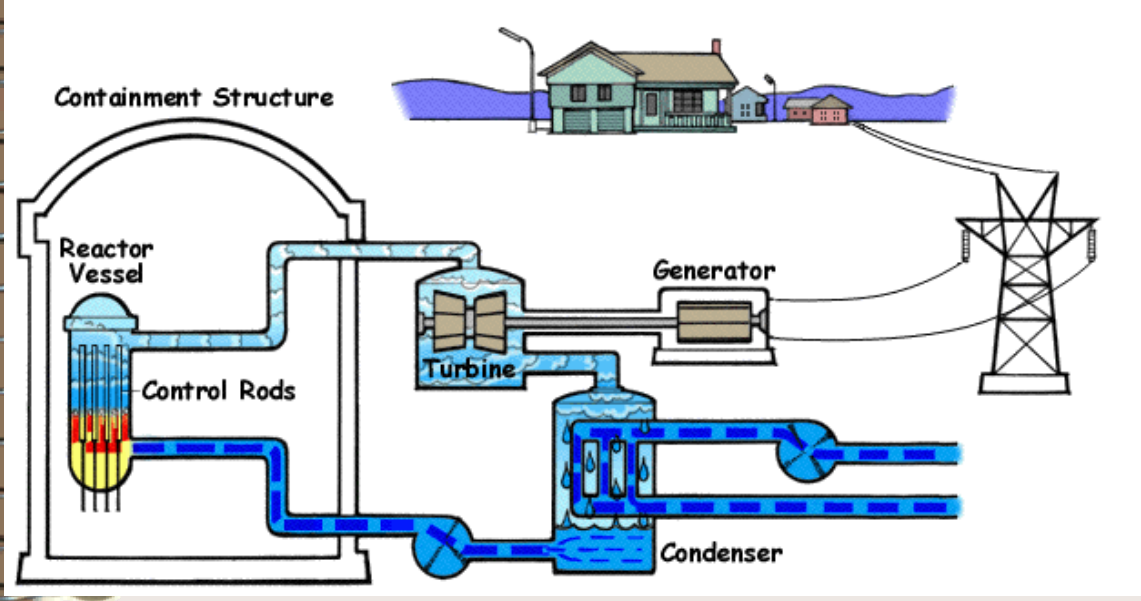
The PWR reactors (cont)

- Negative temperature coefficient of reactivity
- Enriched uranium oxide ~3%; Zircalloy clad
- Low alloy steel pressure vessel
- External boilers (steam generators); ~33% efficient
- Water-cooled and moderated ~150bar and 320 ^{O}C
- Nuclear submarines adopt similar technology



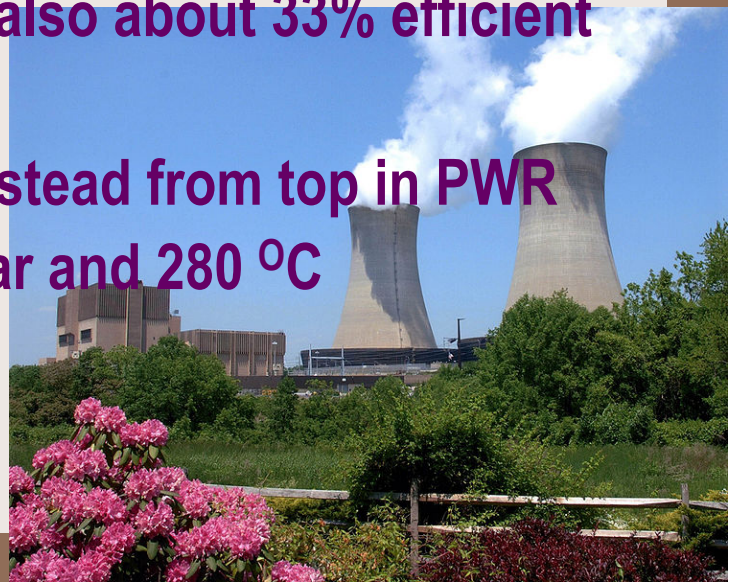
BWR – Boiling Water Reactors

- Water is converted to steam in the reactor and passed directly to the turbine
- Water used is extremely pure with no contaminants to absorb radiation



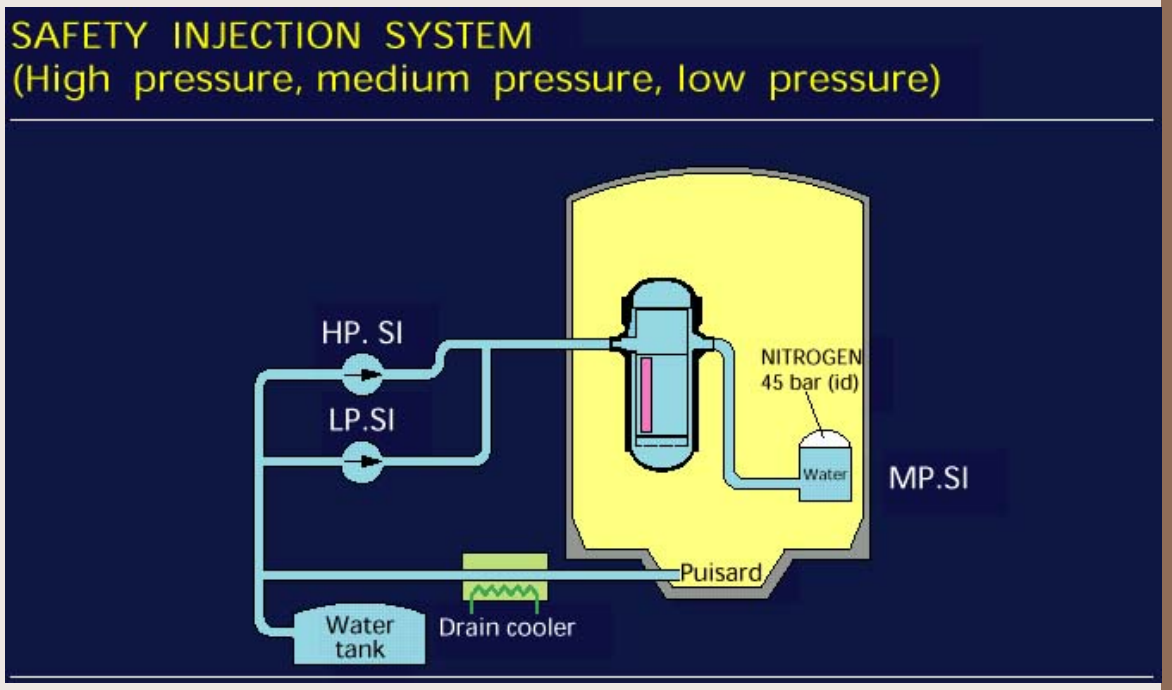
The BWR reactors

- BWR initially thought unsafe due to heat transfer issues – but proved if pressurise system becomes stable
- Negative temperature coefficient of reactivity but not load-following (steam void increases > reduced reactivity)
- Enriched uranium oxide fuel ~2.2%
- Zircalloy clad fuel, low alloy steel pressure vessel
  Simplified plant – only one circuit; also about 33% efficient
- Pressure vessel larger than PWR
- Control rods driven from bottom instead from top in PWR
- Water-cooled and moderated ~70bar and 280 ^{O}C



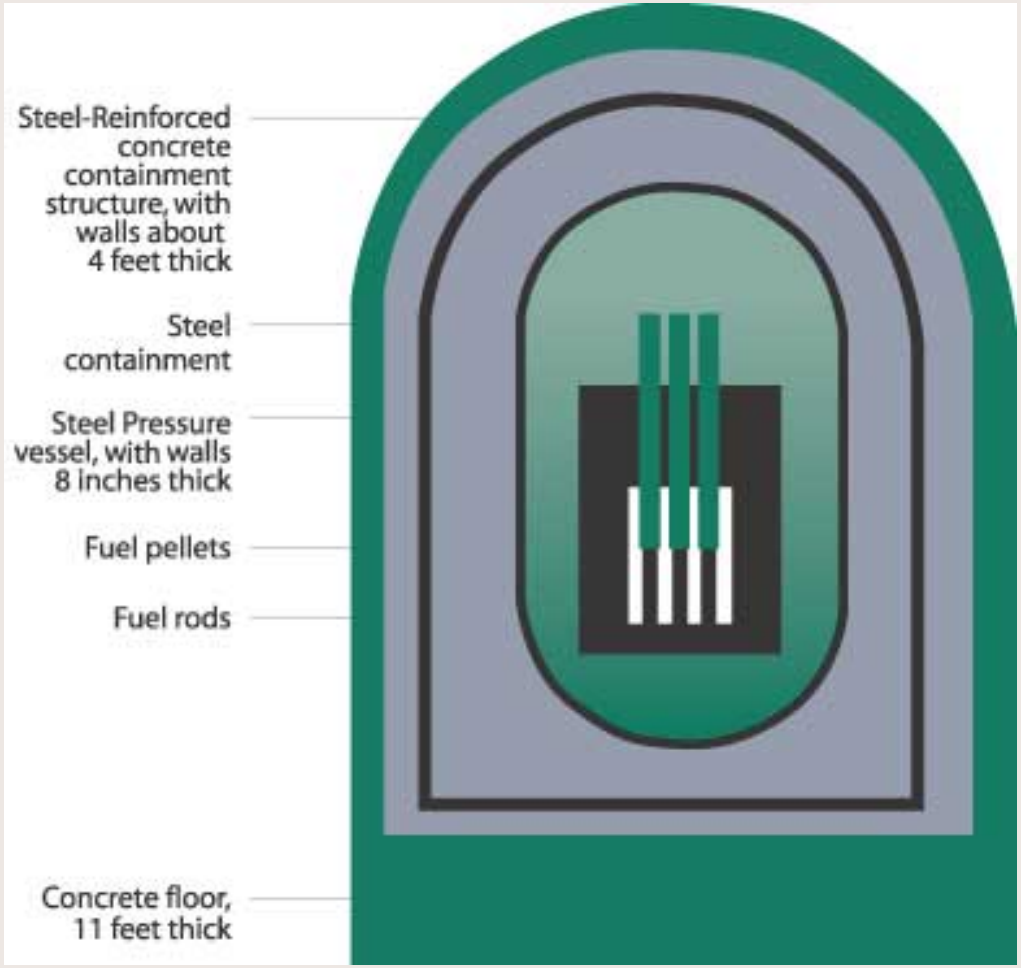
Nuclear safety

- Must prevent core melt (the China Syndrome) by keeping the core cooled – covered with coolant (water) at all time
- Regulatory control
- Inherent safety
- System design



Nuclear safety – “defense in depth”

- Reactor is protected by layers of safety defenses
- Physical safety barriers to contain radiation and provide emergency protection
- Functionally redundant cooling systems with multiple power supplies (offsite, diesel generators, batteries)
- Redundant Control and power cables should be physically separated or “fire wrapped

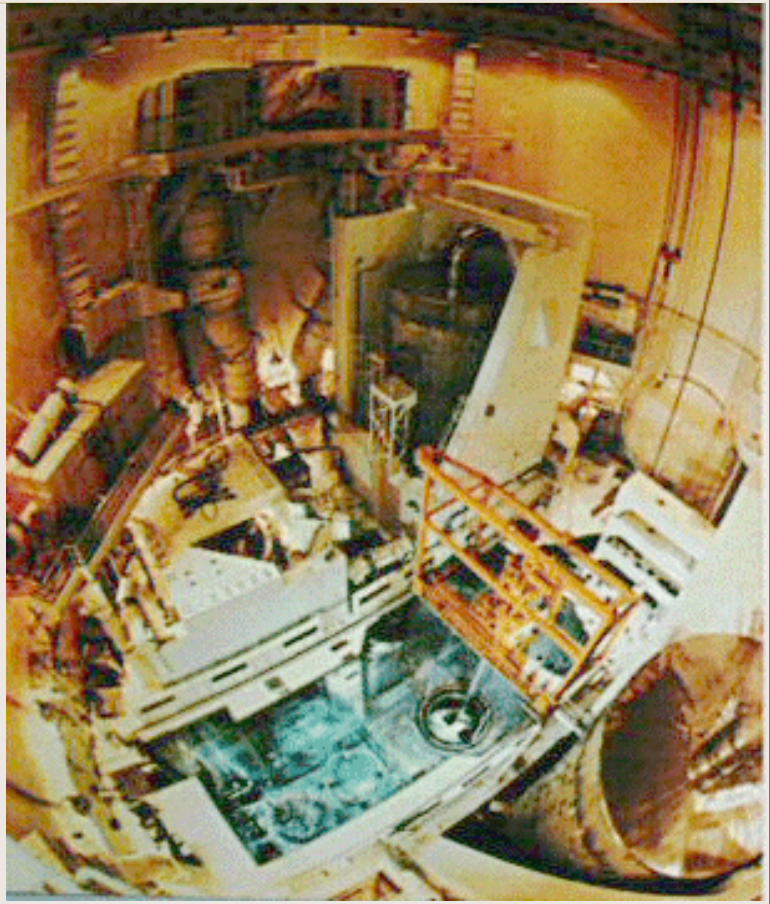


Nuclear safety – “defense in depth”

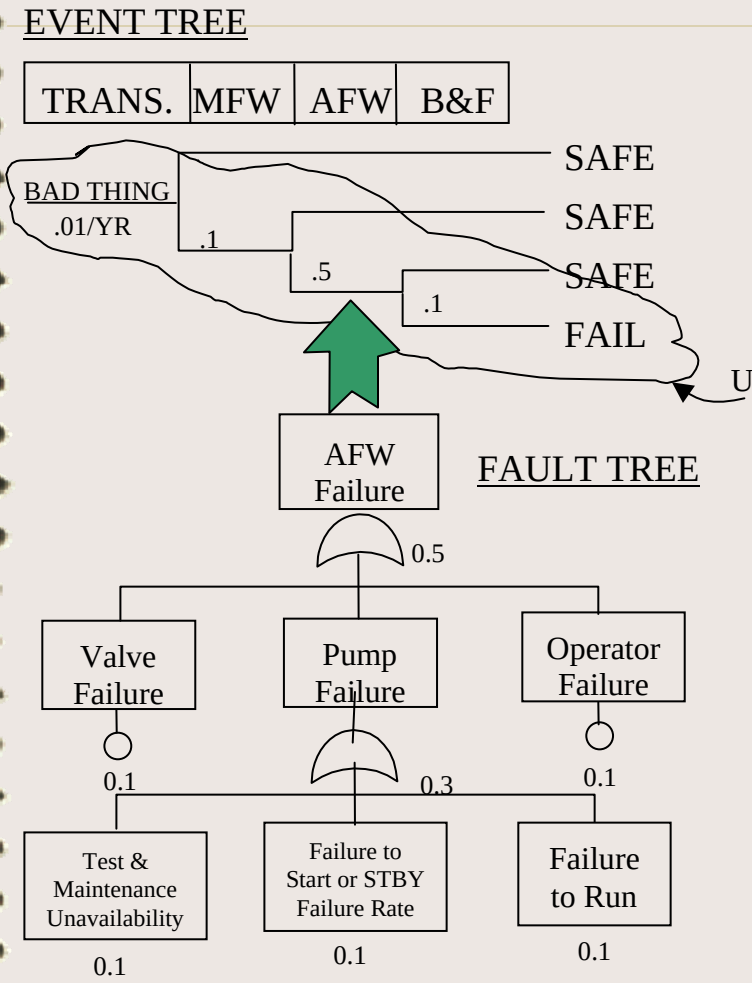
- Multiple, redundant, and independent layers of safety systems in place to reduce the risk of a single, critical point of failure: reactor core meltdown or a catastrophic failure of reactor containment
- Multiple control on chain reaction
- Long-term maintenance for plant safety
- Materials management for reliable plant components
- Plant fire protection receives safety focus
- Industry-wide personnel training program for safe plant operations
- Plant security to protect sabotage and assault

Nuclear safety – risk assessment to prove safety

- Probabilistic risk assessment
- Quantitative risk assessment
- Individual Plant Examination
- IPE for external events
- Risk-based regulations
- Risk-informed regulations



One-minute QRA



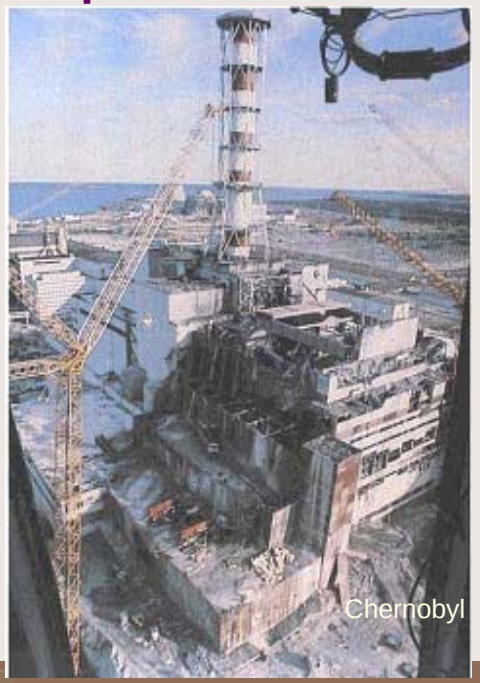
Fail Path Frequency

TRANS MFW AFW B&F

.01/YR X .1 X .5 X .1 = $5X10^{-5}$/YR

Despite all efforts, accidents still happen

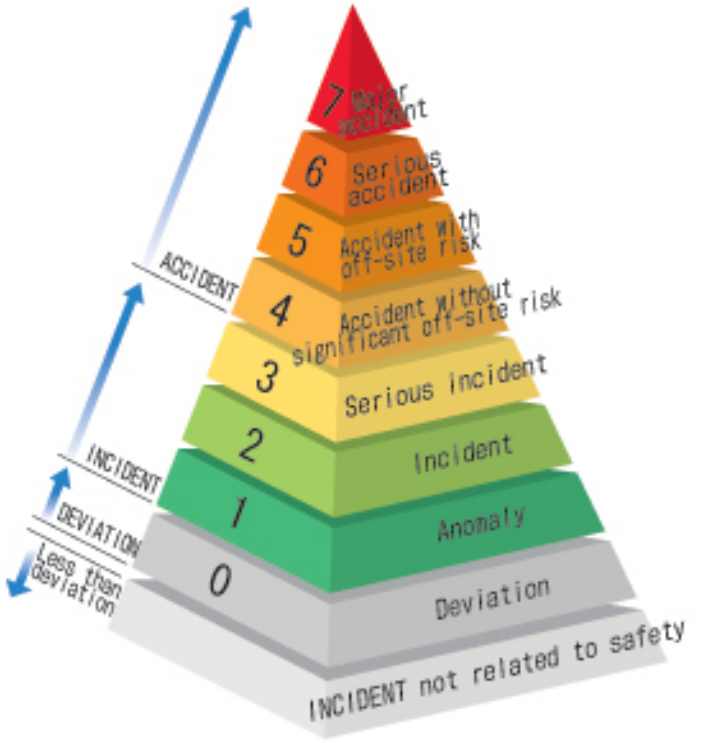
- Although designed with multiple layers of defense, accidents have occurred and will occur
- Reactors cannot blow up like a nuclear weapon; hydrogen explosion is possible


Chernobyl

- Severe accidents are mostly a result of human errors with multiple hardware failures in an unforgiving situation
- Near 2000 fires occurred in NPP; fire can be the initiator or the result of an accident

Nuclear accidents- International Nuclear Events Scale

- inspired by the Richter scale for earthquake, the International Nuclear Event Scale (INES) was introduced in 1990 by IAEA in order to enable prompt communication of safety significance information in case of nuclear accidents
- 7 levels on the INES scale
  - 3 *incident*-levels
  - 4 *accident*-levels



Serious nuclear accidents

- 1952 – First major reactor accident: NRX Chalk River, Canada. Human error. The reactor core was nearly demolished by explosions. Nil fatality, nil environmental effect
- 1957 – Windscale No 1, UK. Fire caused by human error and defective procedures resulted in eleven tons of uranium being ablaze. Nil fatality, wind-spread contamination
- 1975 – Lubmin, E. Germany. Fire at nuclear power complex causes near meltdown
- 1975 – Browns Ferry, USA. Human error. The 7-hr+ fire resulting in nil fatality and nil environmental effect


Browns Ferry Fire, 3-miles away

- 1979 – Three-Miles Island-2, USA. Series of human and mechanical failures lead to partial meltdown. Nil fatality, minor short-term release
- 1986 – Worst nuclear accident in world history. Explosion and fire at Chernobyl nuclear reactor, Ukraine, spews radiation over much of Europe; 31 die instantly, hundreds of thousands affected

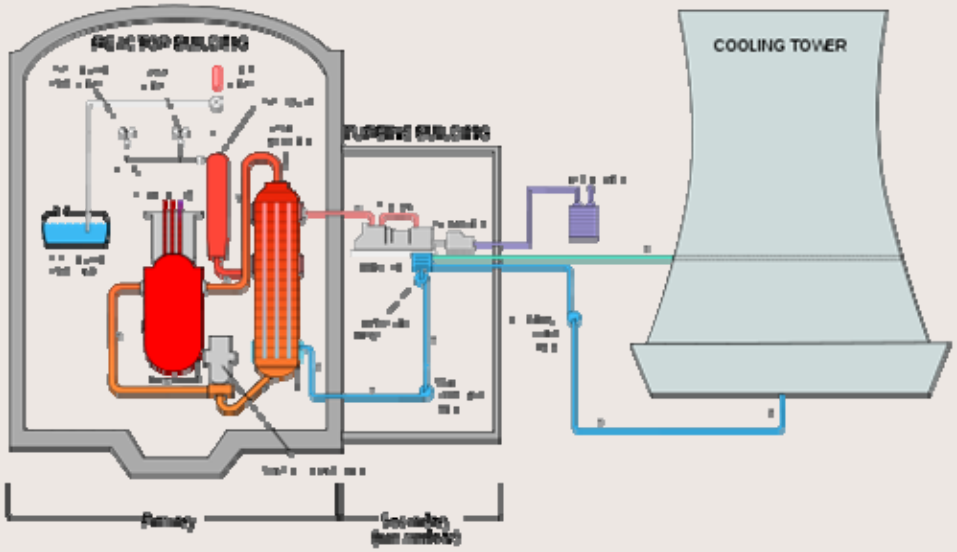
Nuclear accidents – closer to home

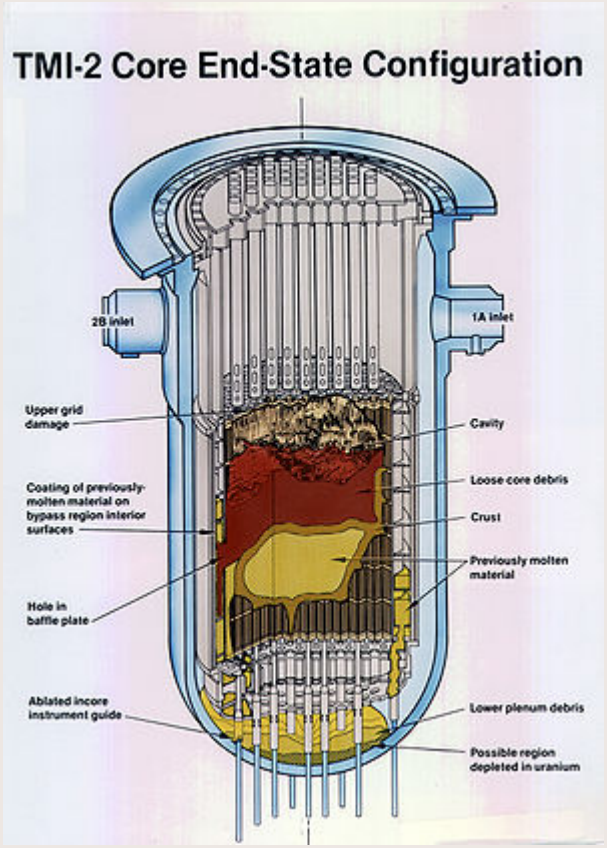
- 1995 – Monju, Japan. Sodium leaks in the prototype fast-breeder nuclear reactor
- 1997 – Tokaimura, Japan. Fire and explosion at state-run Power Reactor and Nuclear Fuel Development Corp. reprocessing plant at, Japan. At least 35 exposed to radiation
- 1999 – Tokaimura, Japan. Workers trigger nuclear reaction by mixing too much uranium into storage tank. At least 55 exposed to radiation

Susquehanna

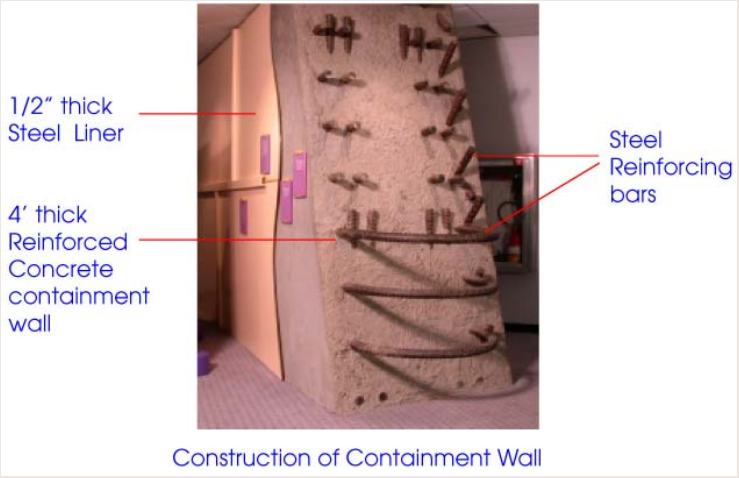
- 2001 – Third NPP, Taiwan. Electrical equipment failure shuts down the plant. Two backup diesel generators fail. 8-hr battery, almost depleted, keeps core away from meltdown
- 12 June 2009 Taipei - A fire broke out at a Taiwan nuclear power plant, no one was injured and there was no radiation leak, Taiwan's Atomic Energy Council said in a statement.

Three Mile Island

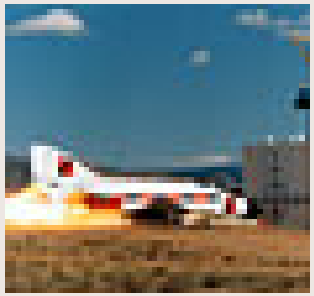




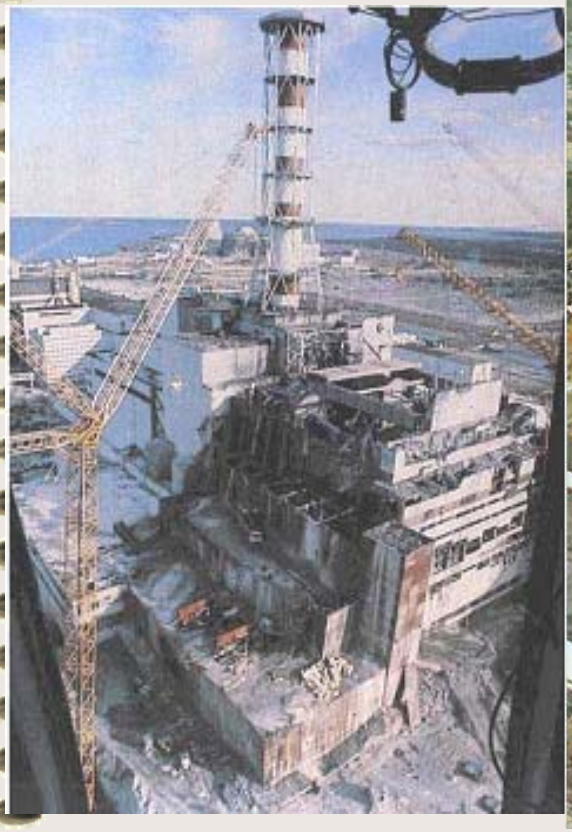
Protected by thick containment wall to prevent release to public

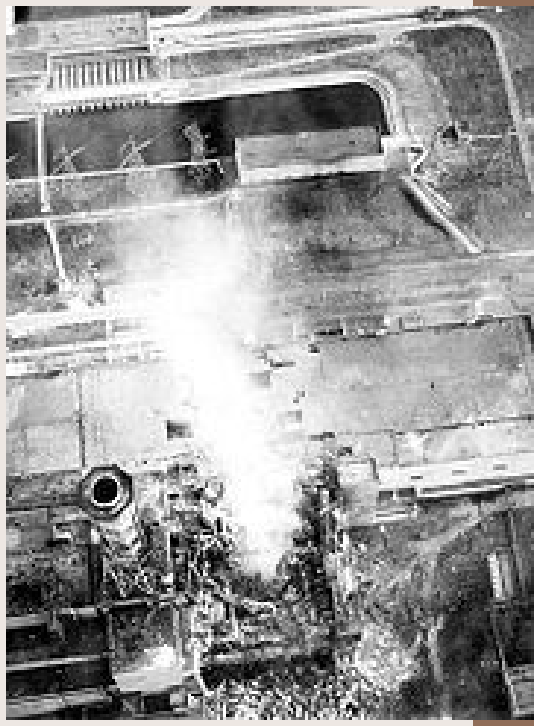


Construction of Containment Wall



When there is no containment, compounded with an unsafe culture …

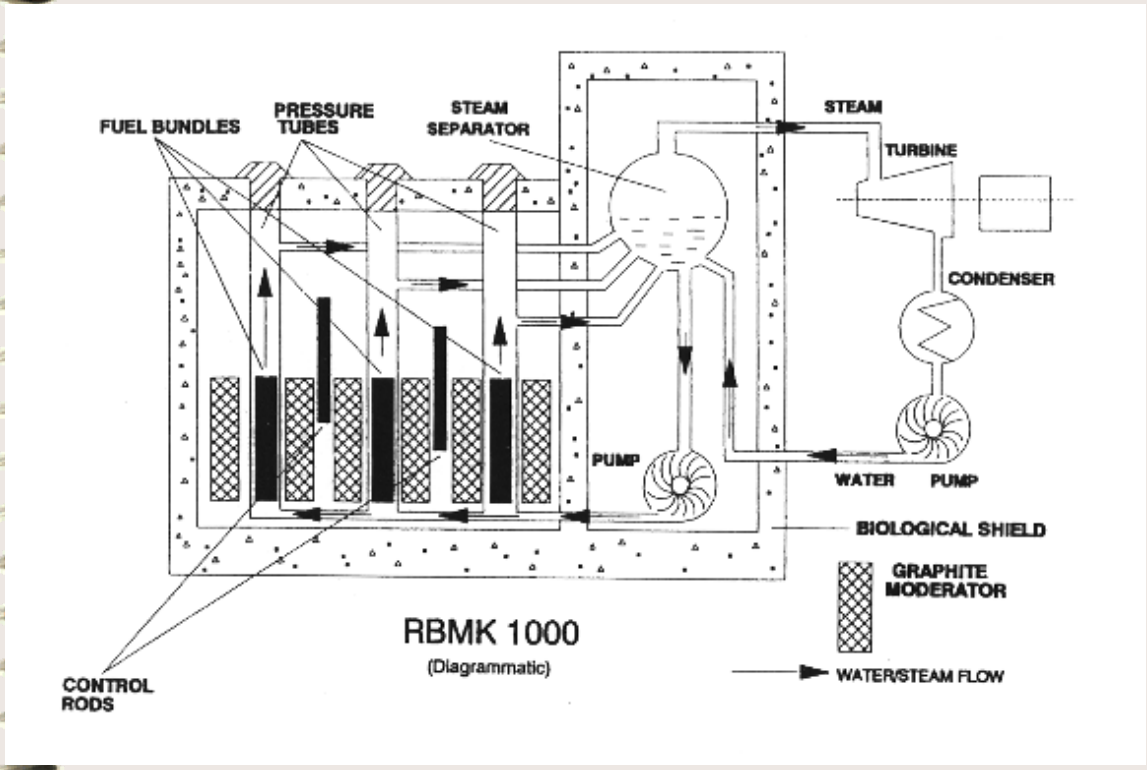




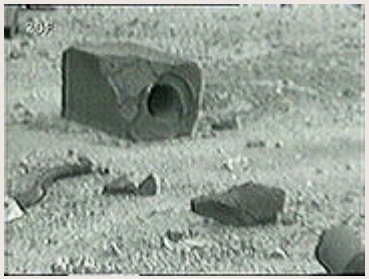
We have the worst nuclear disaster at Chernobyl

Chernobyl

Chernobyl



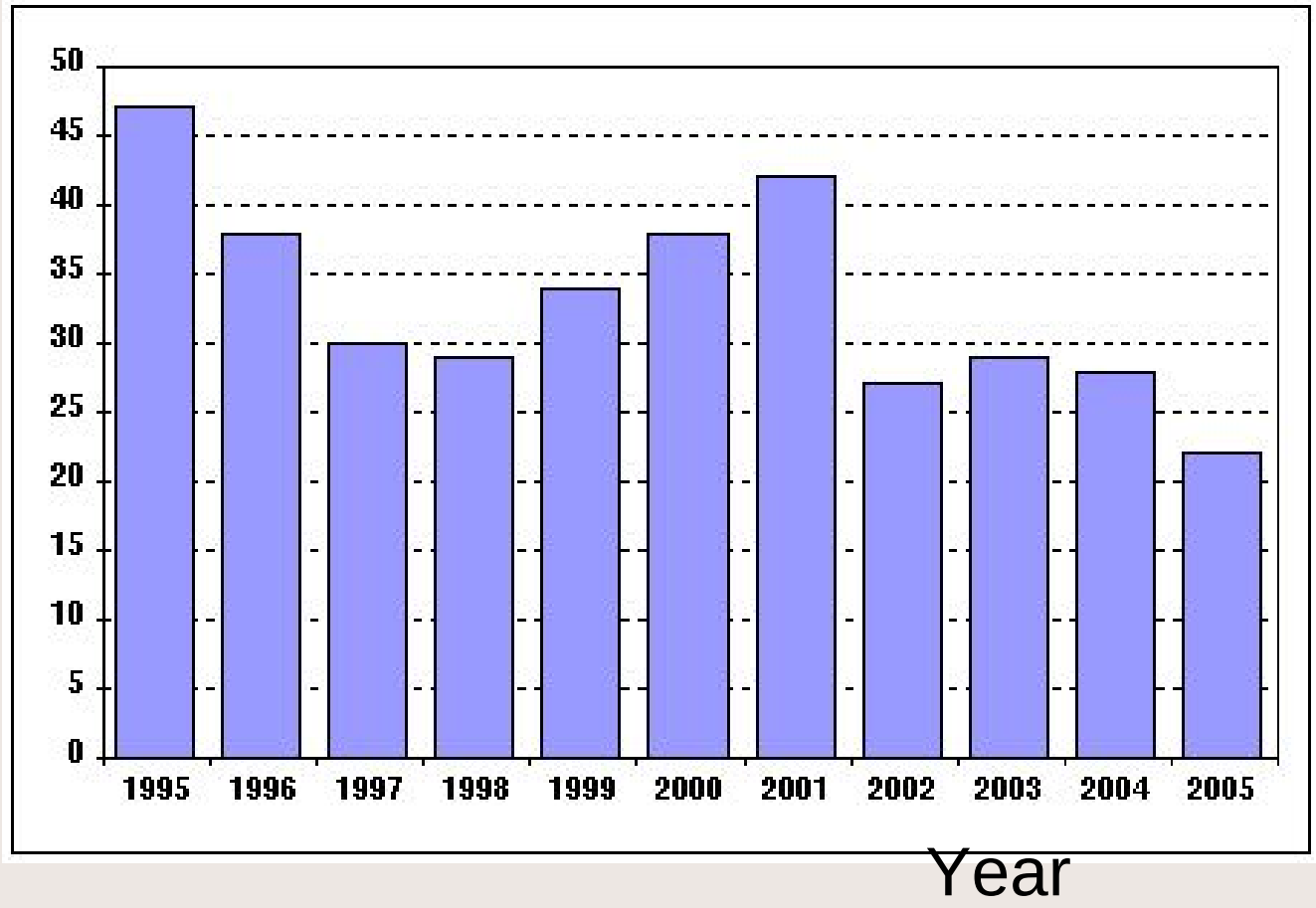
RBMK 1000
(Diagrammatic)



Relative share of accidental fatalities in the stages of various energy industries

	Coal	Oil	Natural Gas	Hydropower	Nuclear
Exploration and production / processing	Explosions and fires in coal mines	Well blowouts, accidents on drilling platforms at sea.	Well blowouts, accidents on drilling platforms at sea.		
Transportation		Tanker accidents at sea	Pipeline accidents		
Processing / storage		Process accidents in refineries and tank farms			
Regional / local division		Overturning and collisions of tank trucks	Pipeline accidents		
Powerplant or heat production			Process accidents	Overflow or failure of storage dams	Core meltdown with large release of radioactivity
	0–5%	5–15%	15–30%	30–60%	60–100%

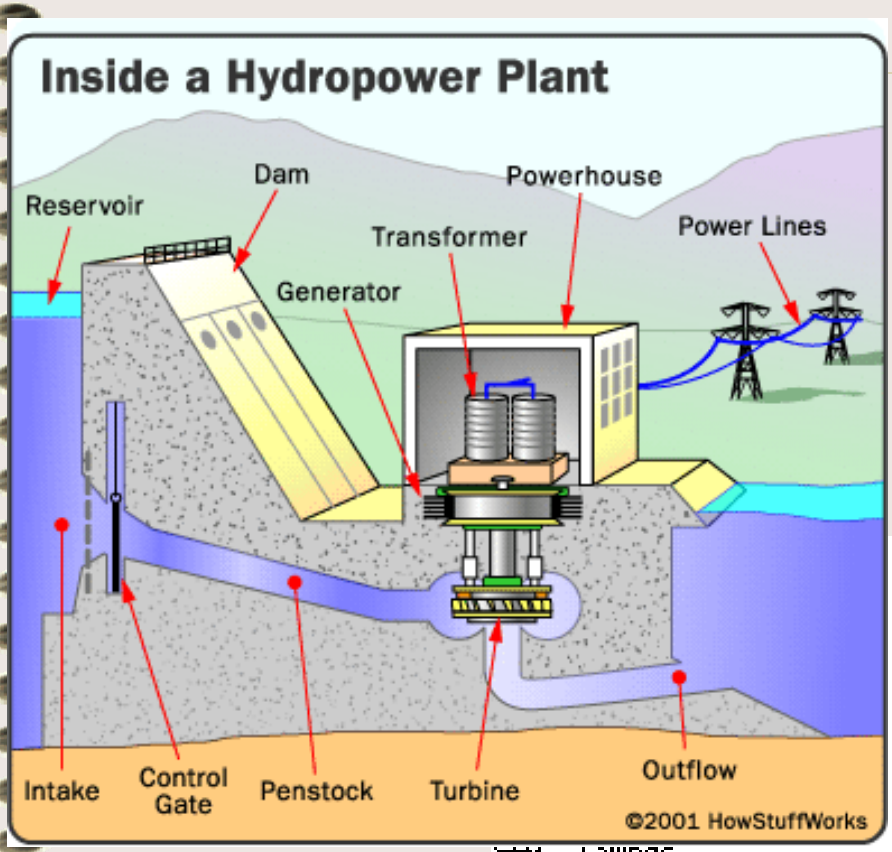
Fatalities in US coal mining



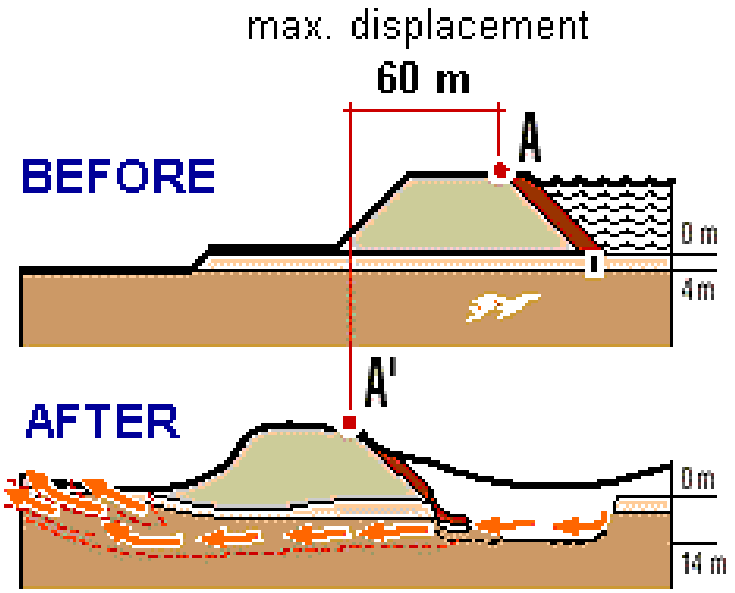
Coal mining: The most deadly job in china

- China produced 35 percent of the world's coal last year, but reported 80 percent of the total deaths in coal mine accidents, according to statistics with the State Administration of Work Safety (SAWS)
- Among accidents occurred from January 2001 to October 2004, there were
  - 188 each with death toll of more than 10, about one death every 7.4 days, said SAWS Wang Xianzheng at a national meeting on coal mine safety.
  - One month in 2004 along, there were a series accidents reported with over 200 deaths
- China's coal-mining industry is among th most dangerous in the world, resulting in the deaths of more than 2,600 workers in the first half of 2005 alone

Hydro-power accidents



Tailings
Impermeable layer
Rockfill dam
Bentonite-cement seal
Quaternary. Terrace and alluvial
Tertiary. Grey-bluish marls
Plane of rupture and fractures
Direction of displacement



Consequences of Dam Failures

- Consequences of dam failures can be devastating
- Can lead to thousand of death and regional economic breakdown

- The disappearing of a village or a town is not uncommon
- Significant environmental impact at national scale

Banqiao Dam 板桥水库 / Shimantan Reservoir Dam (石漫滩水库)

- The Banqiao Dam 板桥水库 was built in the early 1950s on the Ru River as part of a project to control flooding and generate electricity and as a response to severe flooding in the Huai River Basin in 1949 and 1950
- In August of 1975, however, a 1-in-2,000 year flood occurred, poured more than a year's rainfall in 24 hours (new records were set, at 189.5 mm rainfall per hour and 1,060 mm per day

Banqiao Dam 板桥水库 / Shimantan Reservoir Dam (石漫滩水库)

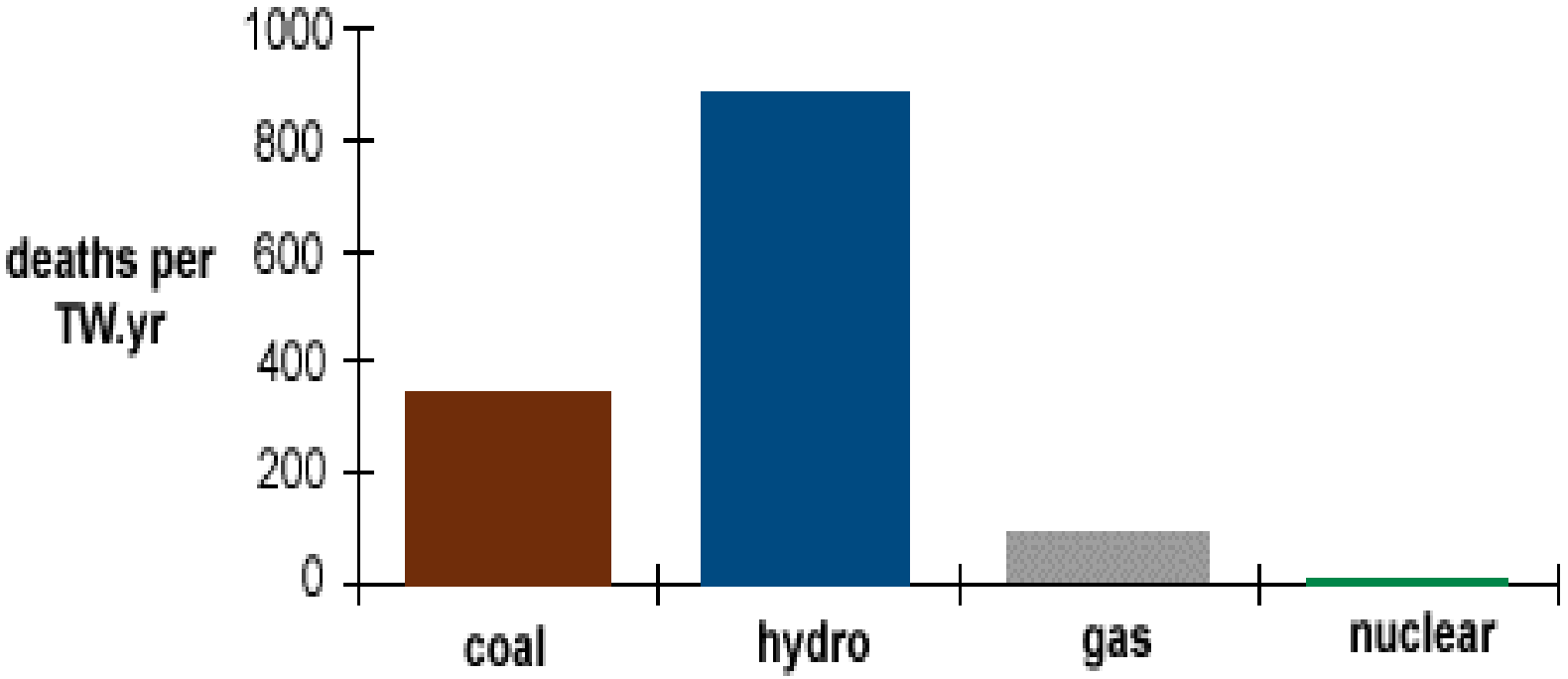
- On August 6, a request to open the dam was rejected, because of the existing flood in downstream areas. On August 7, however, the request was accepted, but the telegraphs failed to reach the dam

- According to the Hydrology Department of Henan Province, in the province, approximately 26,000 people died from flooding and another 145,000 died during subsequent epidemics and famine. In addition, about 5,960,000 buildings collapsed, and 11 million residents were affected

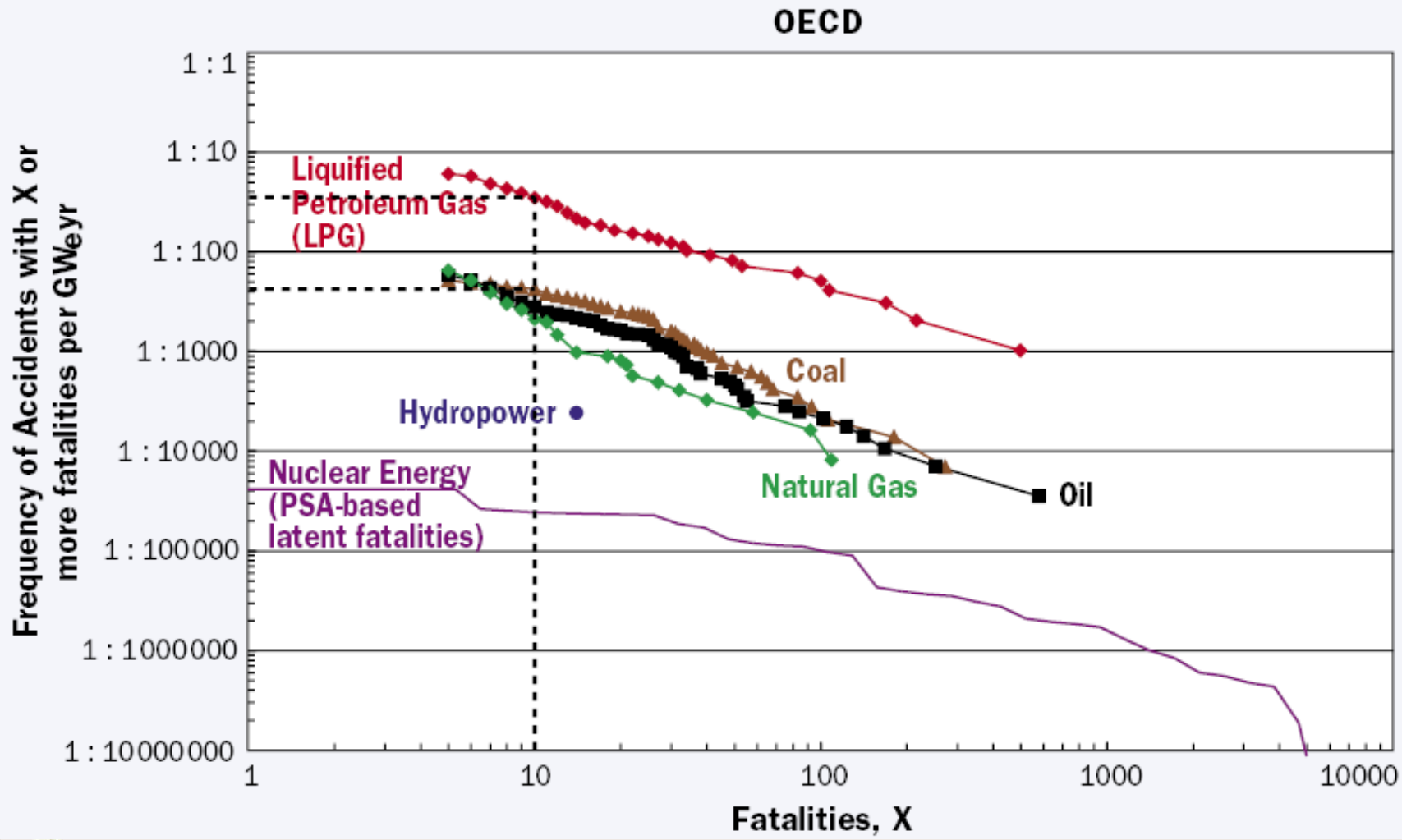
What I Saw….

Floodgate failure

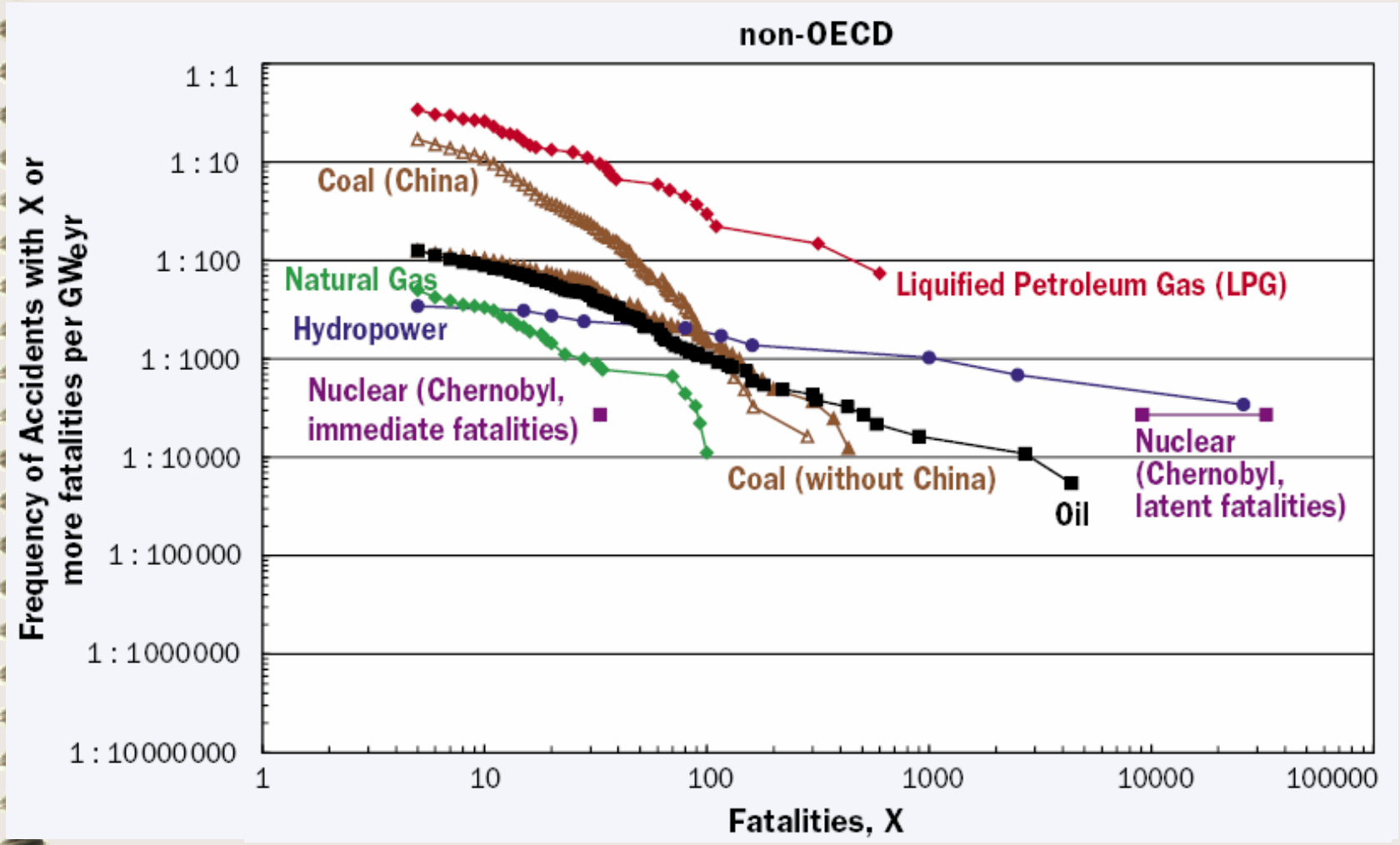
A comparison of energy-related fatalities



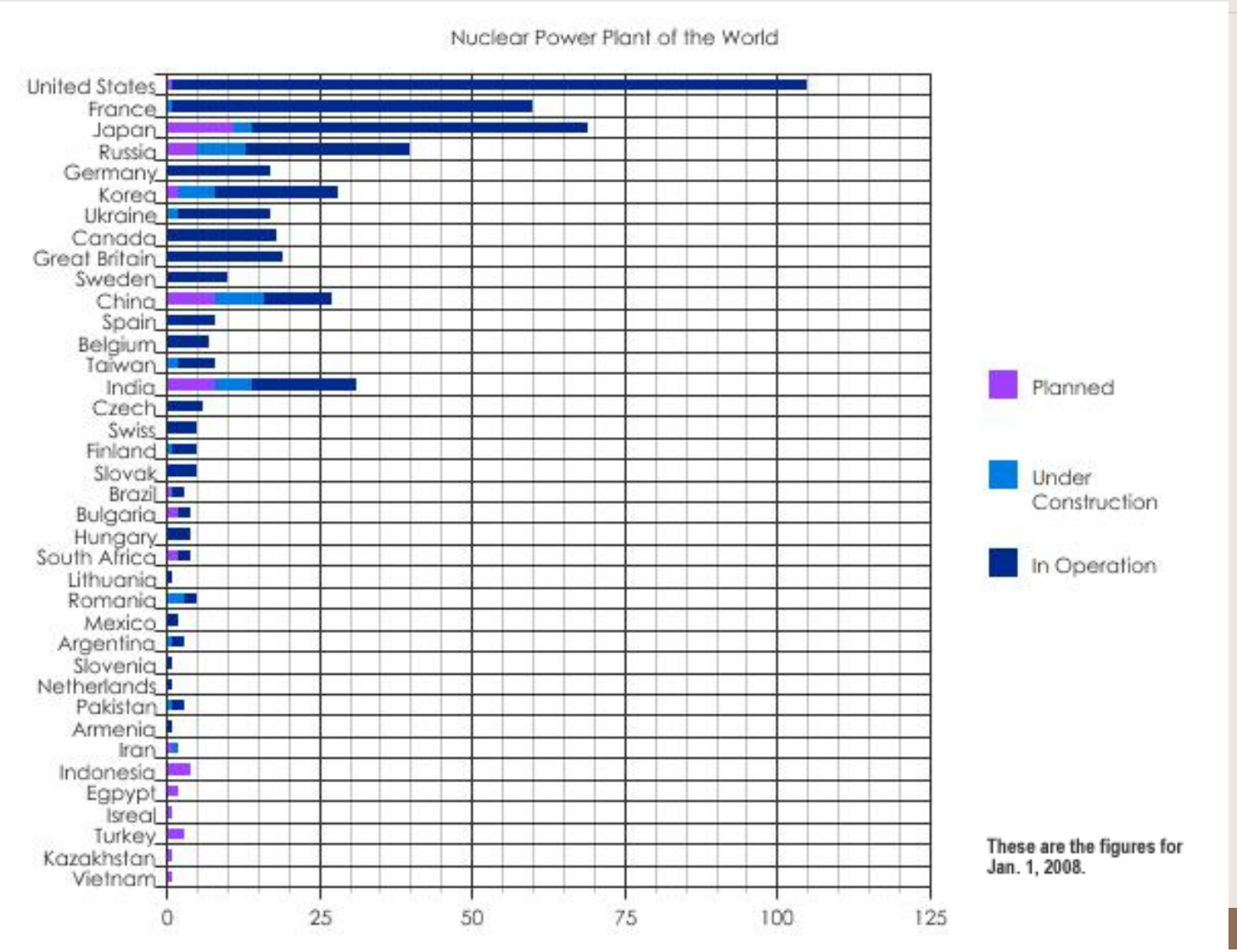
FN curves for OECD energy accidents



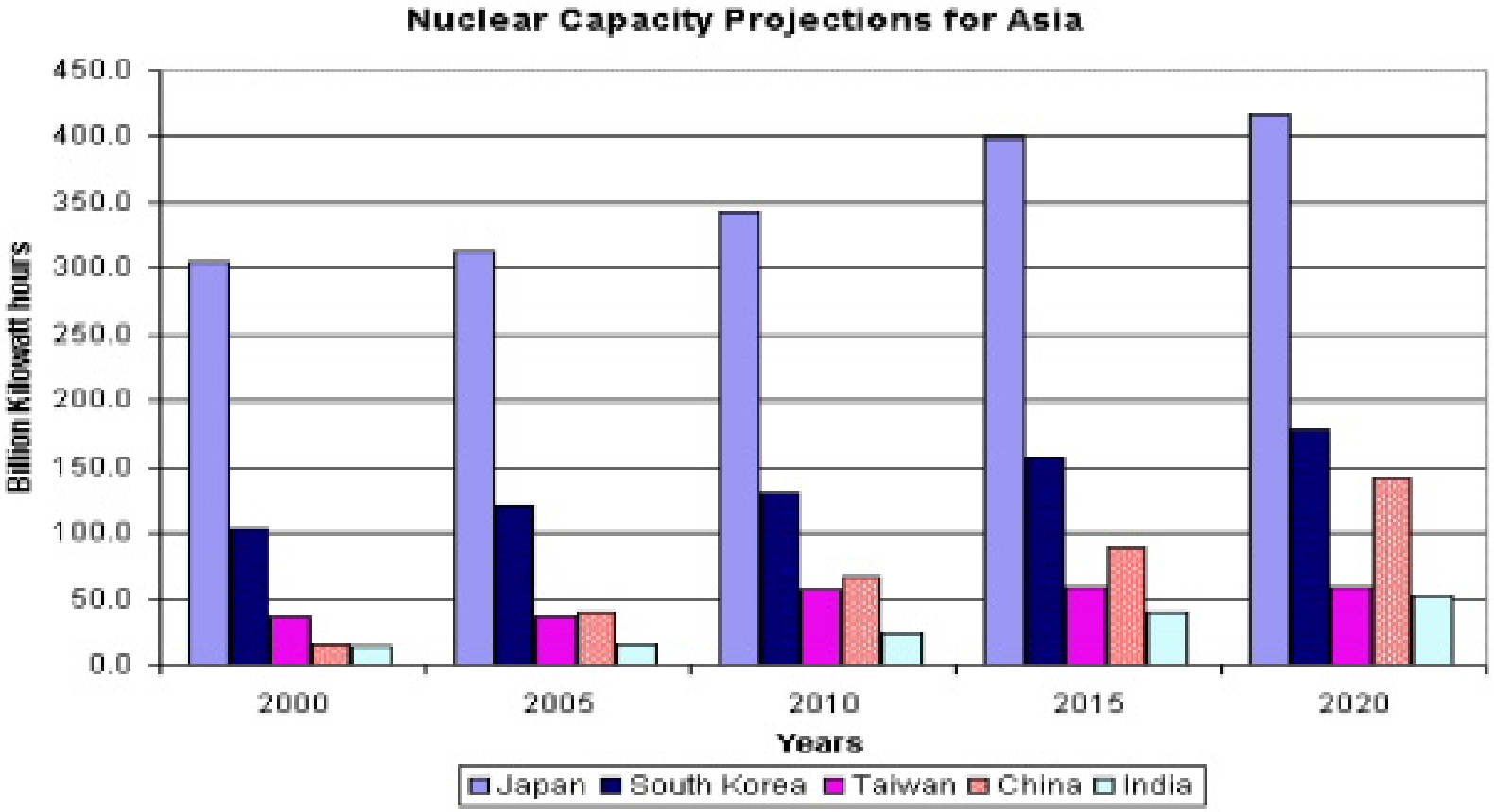
FN Curves for Non-OECD Energy Accidents



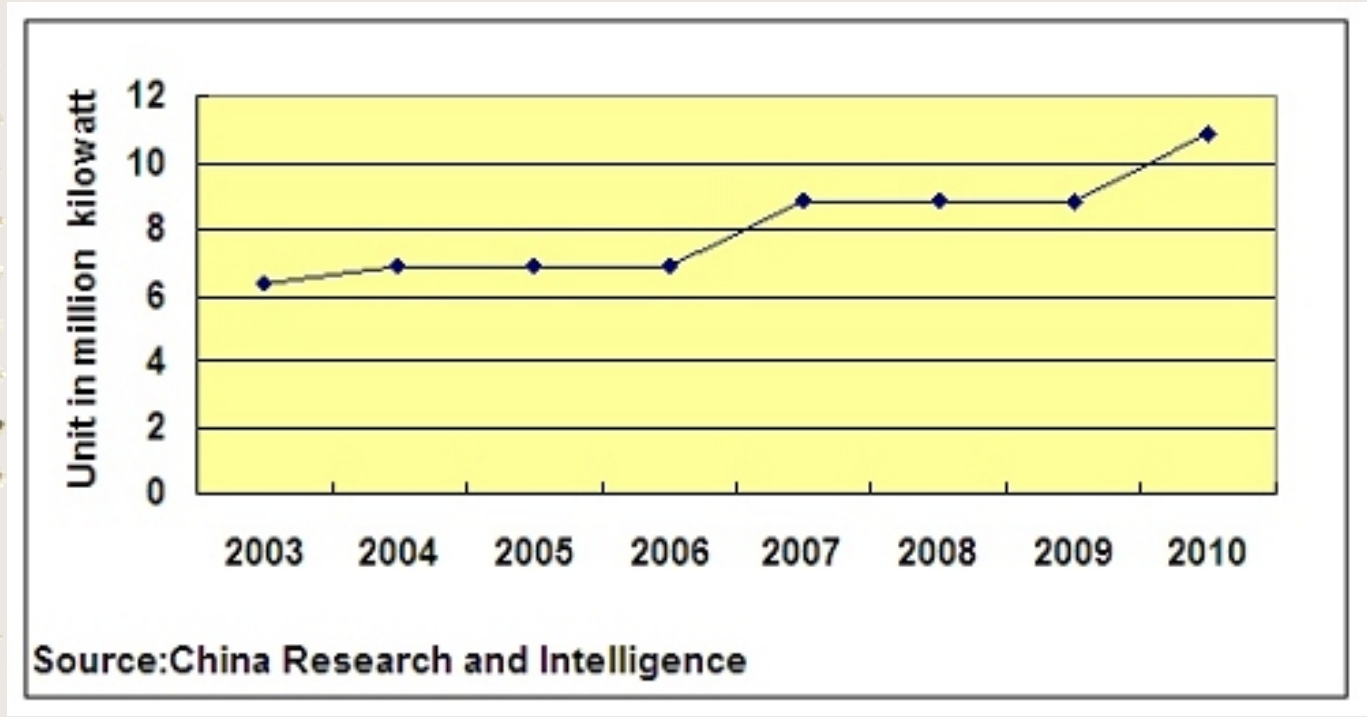
Current world nuclear power profile



Outlook: Steady growth in nuclear capacity

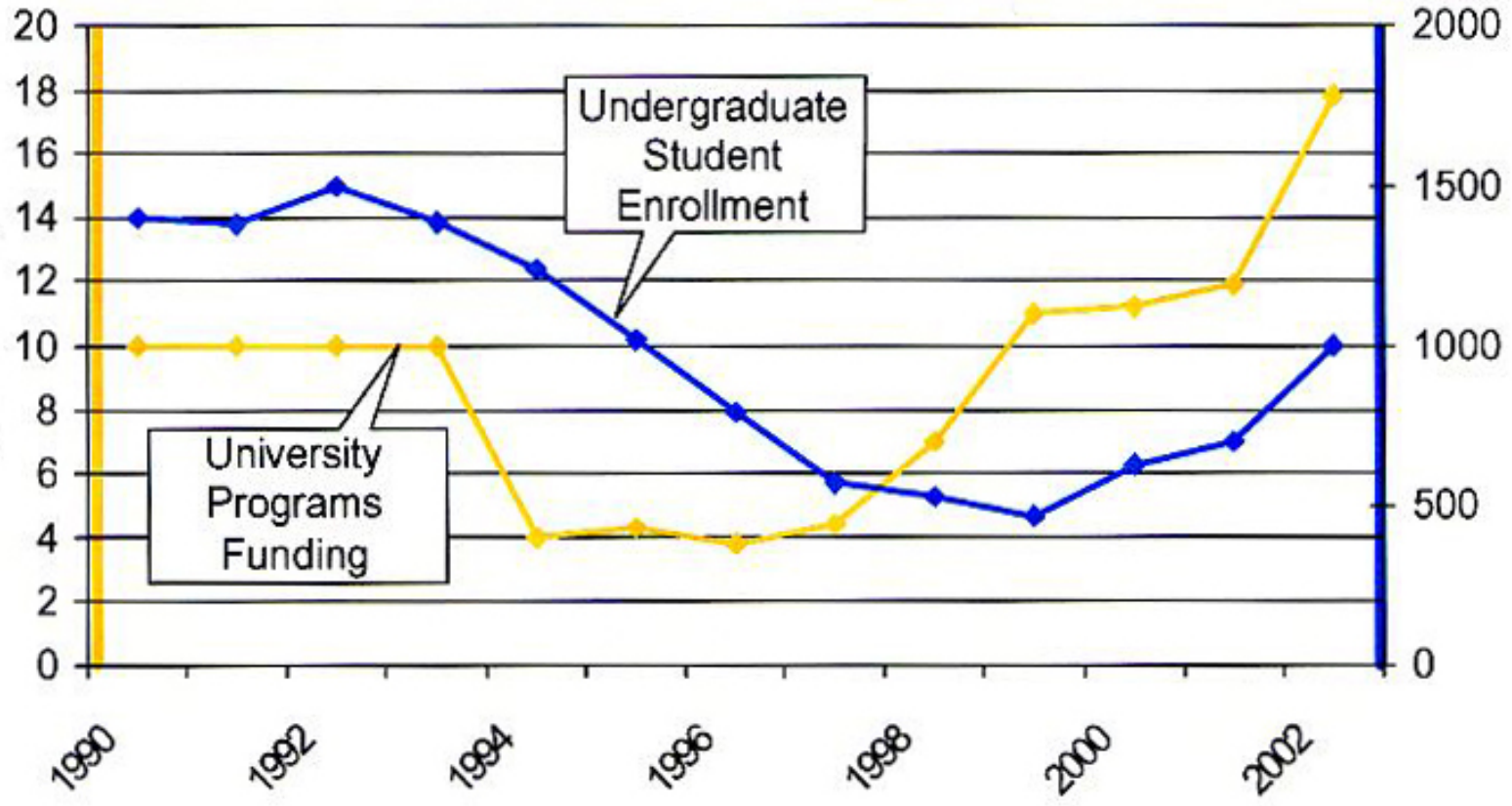


Nuclear energy in China

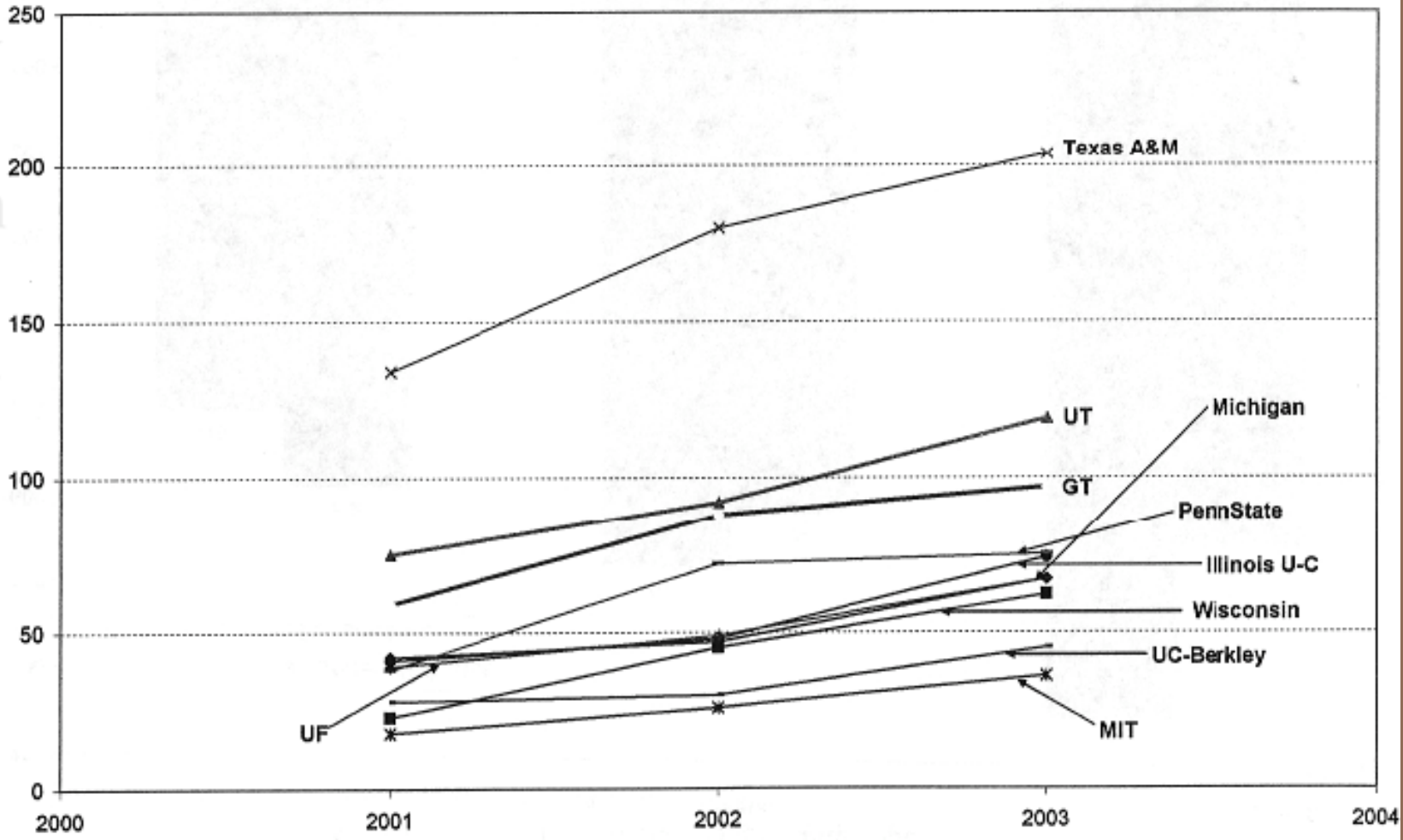


Estimated 35 to 60 reactors will be built in the next 30 years to meet the demand

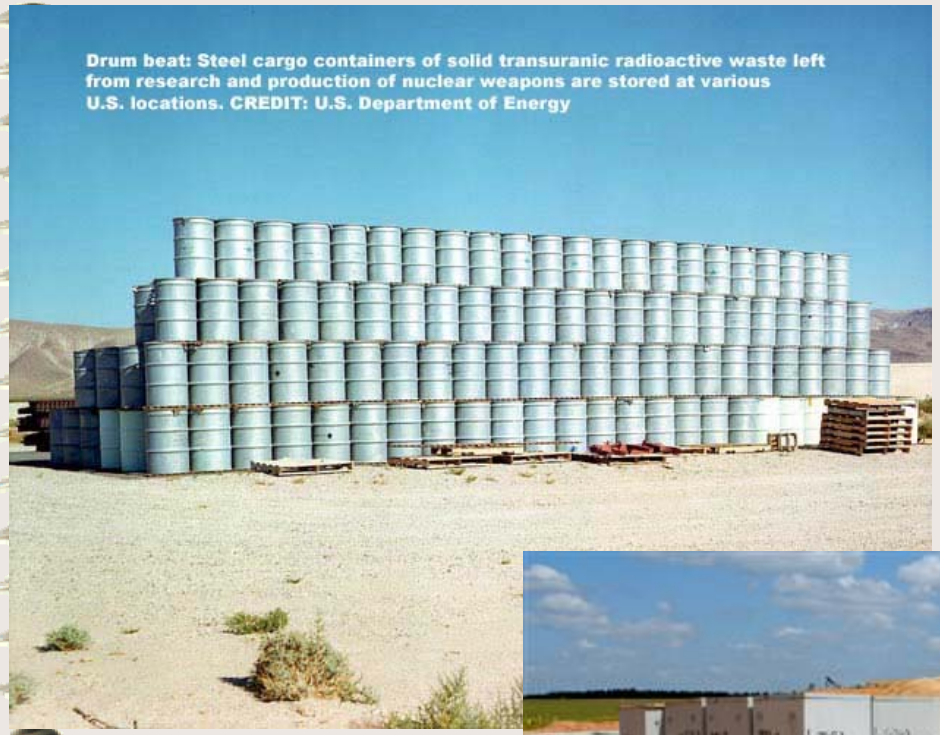
Outlook: University programs in USA



Student enrolment is on the rise

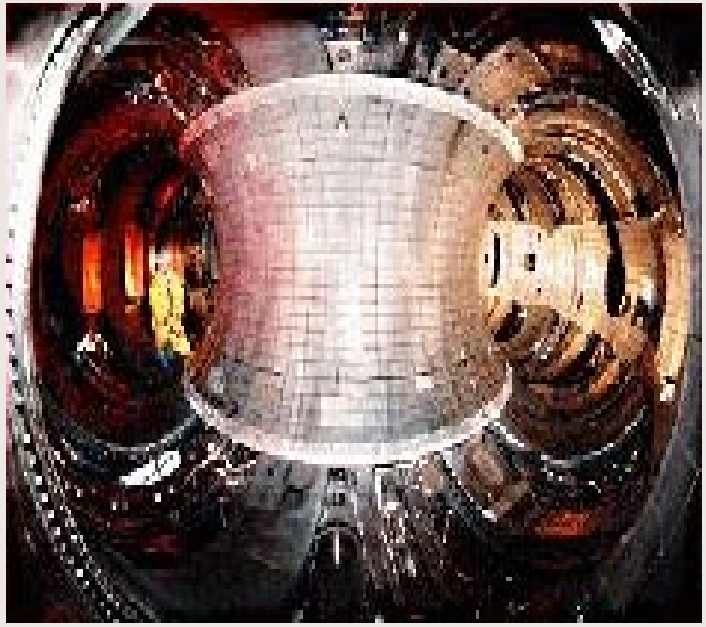


Future of nuclear energy depends on the control of radioactive waste



Drum beat: Steel cargo containers of solid transuranic radioactive waste left from research and production of nuclear weapons are stored at various U.S. locations. CREDIT: U.S. Department of Energy

Could Nuclear Fusion work on Earth?



- Scientists are trying to produce energy by nuclear fusion
- Changing Hydrogen into Helium
- Promise of fusion power is enormous:
  - CLEAN and SAFE source of energy
  - Limitless supply of fuel
  - No significant nuclear accident
  - Less long-lived radioactive waste
- Need to heat and contain gaseous fuel to 10E6 deg C
  - Plasma in magnetic chamber (TOKAMAK)
  - JET – 1983 UKAEA,
  - ITER-FEAT – post 2003
- …always 50y away

Once again, a nuclear reactor cannot explode like a nuclear weapon!!

Did you have a good time?

End