Nuclear Options for Our Energy Future

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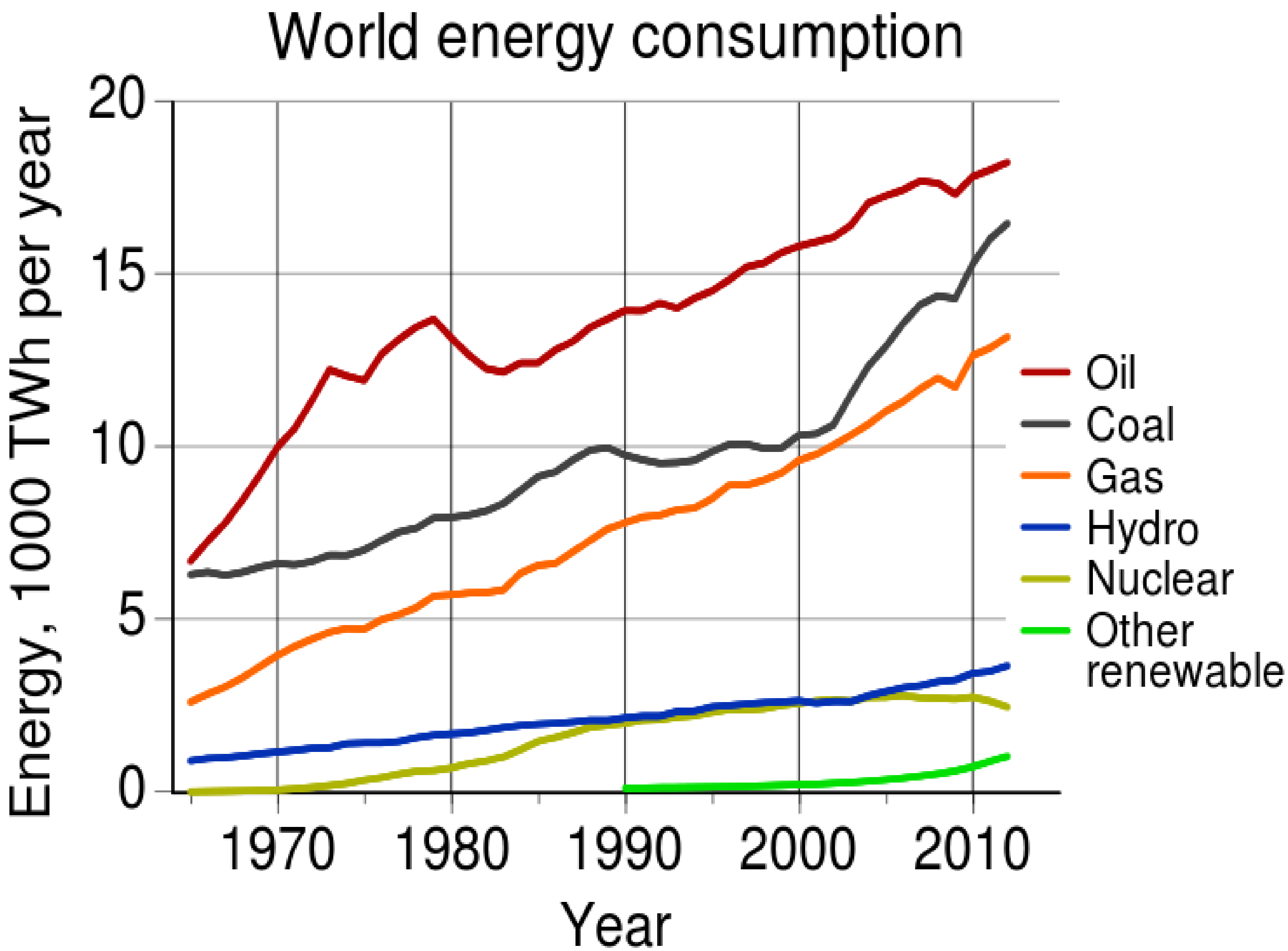
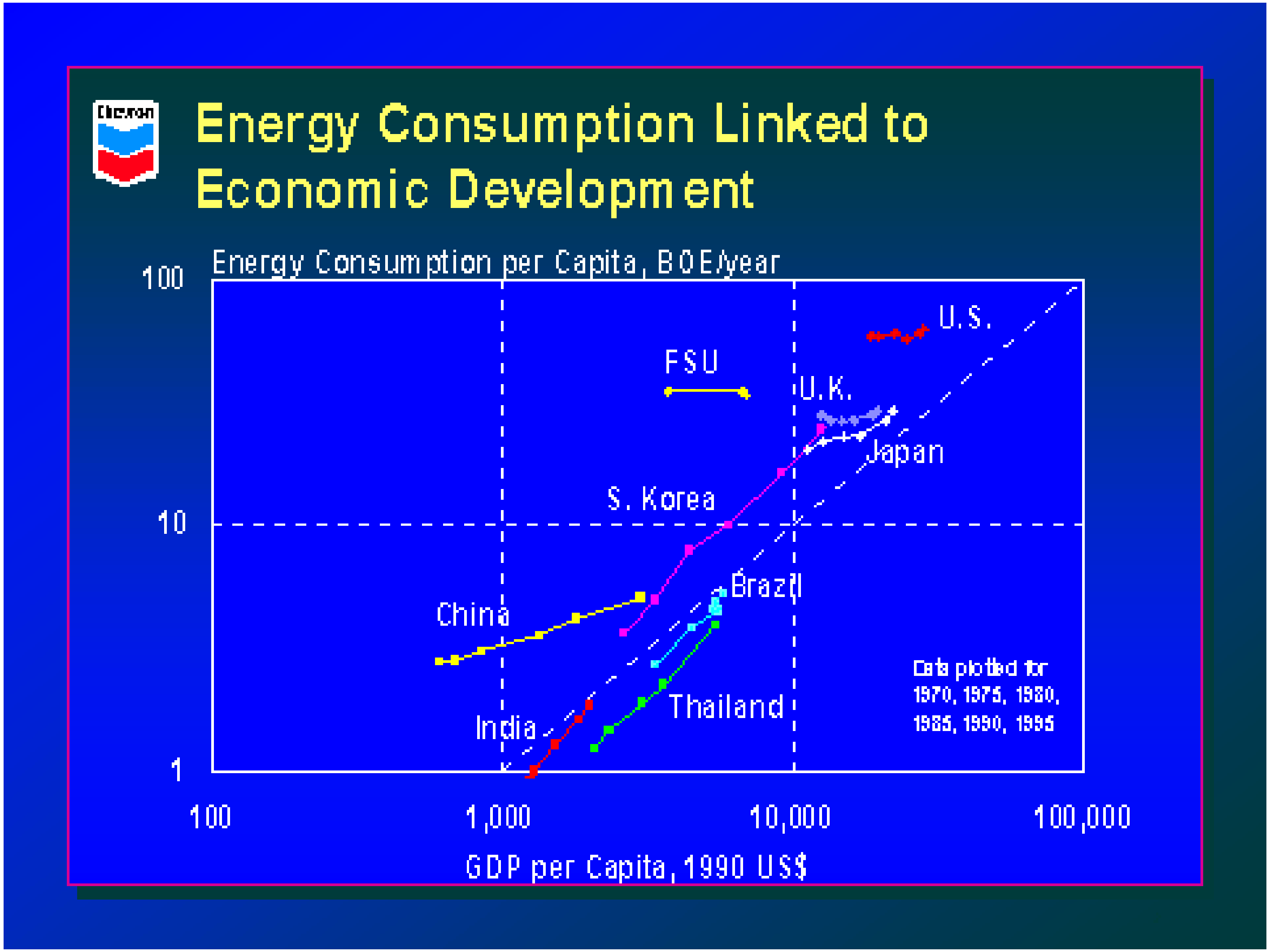
Outline

- Current electricity generation situation
- What is “nuclear power”.
- Fission versus fusion.
- Current status.
- Advantages and disadvantages.
- Generation IV reactors and beyond.
- The political issues.
- Decommissioning.
- High Level Nuclear Waste - Is waste a problem or is the “tail wagging the dog”?



World energy consumption
Energy, 1000 TWh per year
20
15
10
5
0
1970
1980
1990
2000
2010
Year
Oil
Coal
Gas
Hydro
Nuclear
Other renewable



Preaching to the developing nations that they should curtail their demand for energy will not work, because of their desire to improve their standards of living.

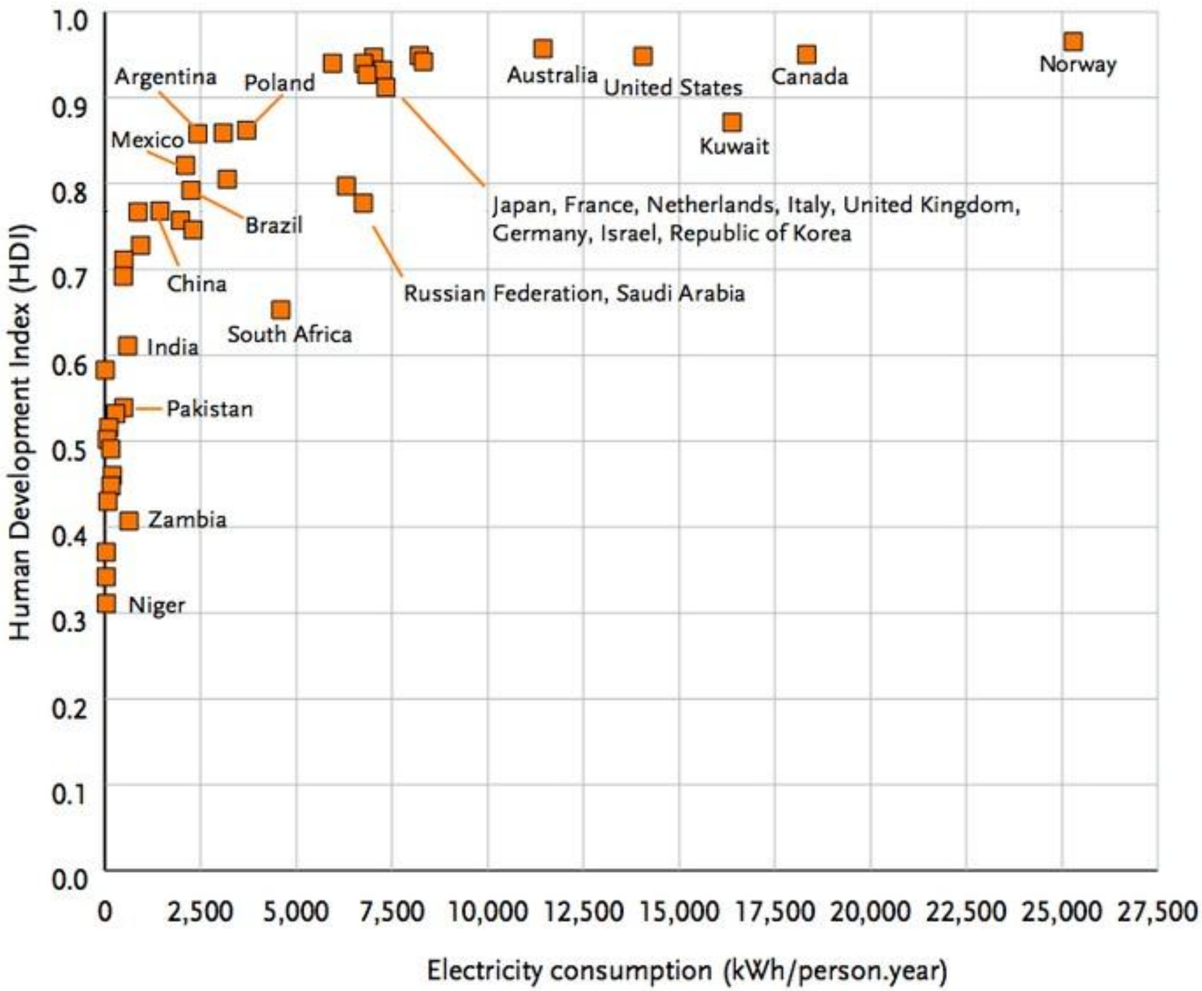


Figure 1.6 Relationship between human development index (HDI) and per capita electricity consumption, 2003 – 2004

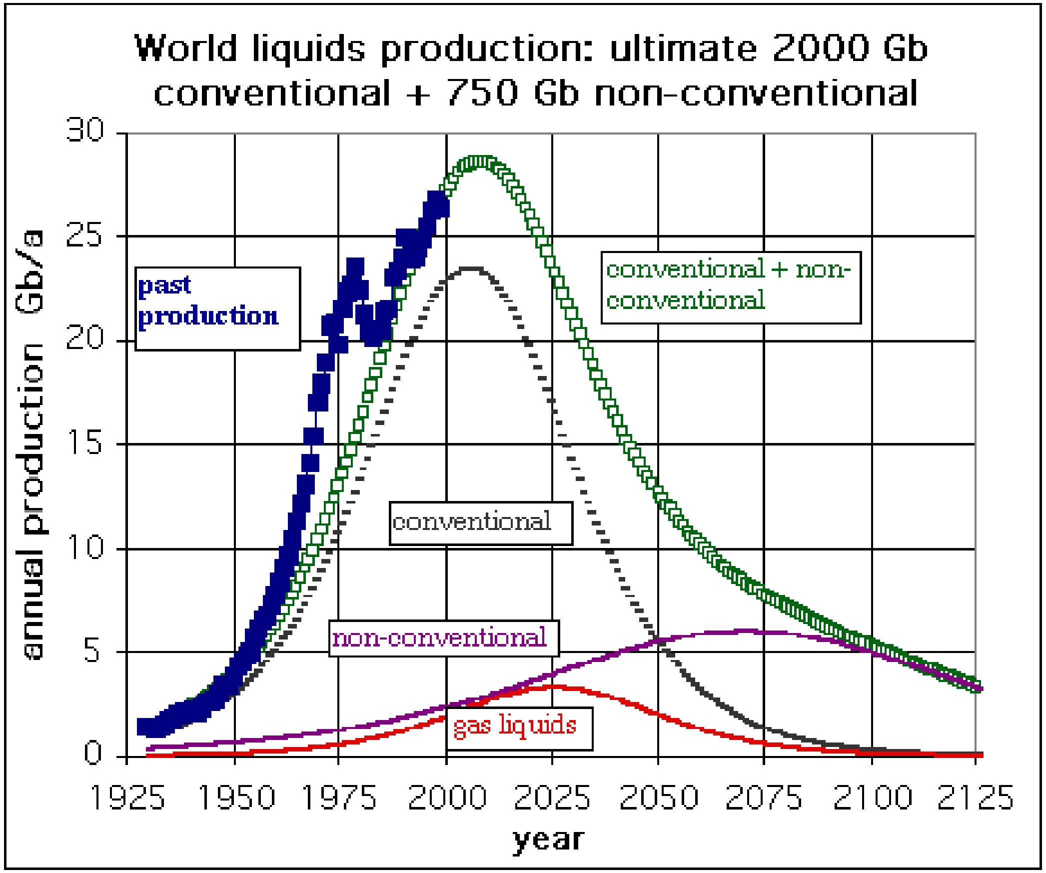
Note: World average HDI equals 0.741. World average per capita annual electricity consumption, at 2,490 kWh per person.year, translates to approximately 9 gigajoules (GJ)/person.year [10,000 kilowatts (kWh) = 36 GJ]

Source: UNDP, 2006.

Oil & Energy OVERVIEW

Oilberta = Energy

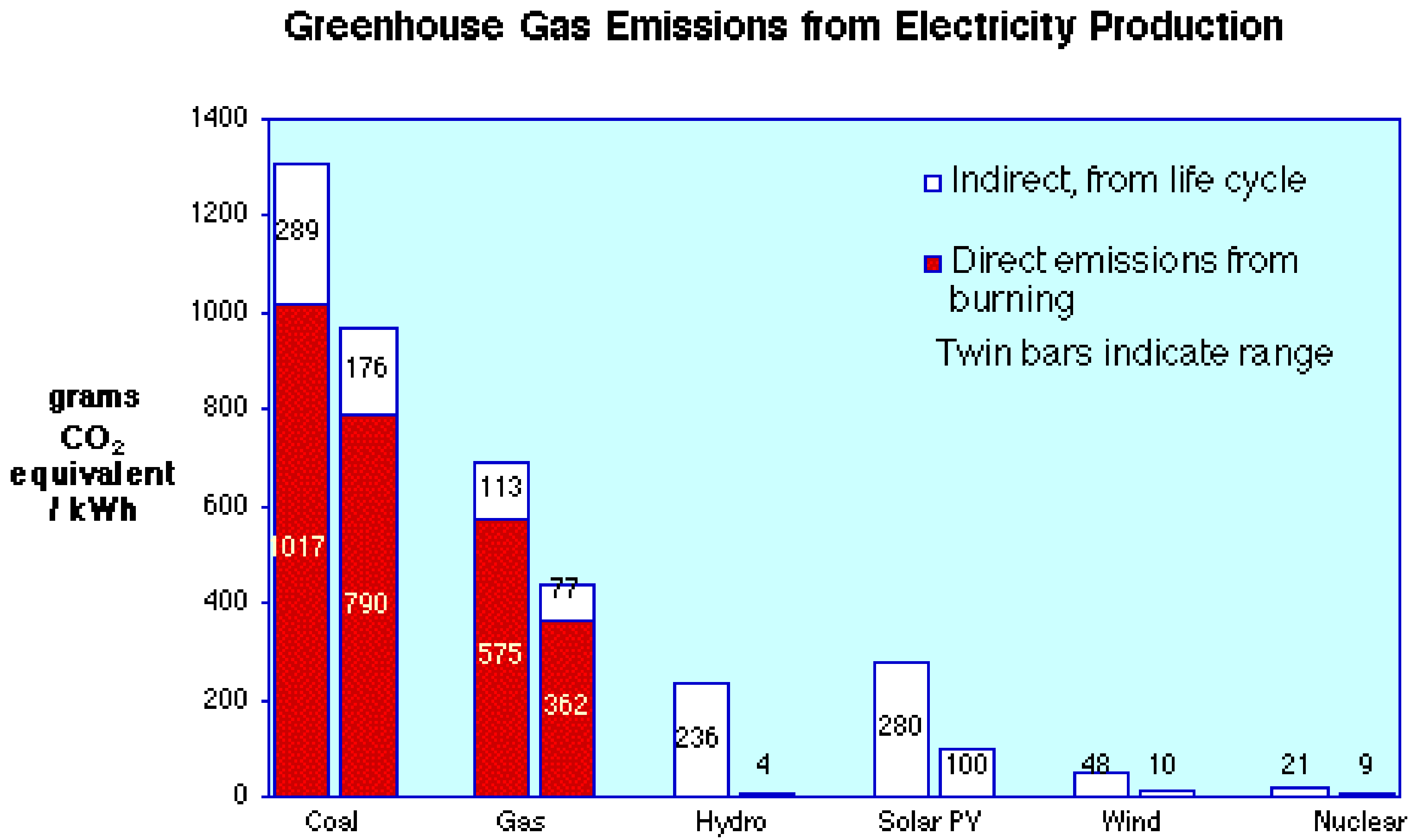
THE HUBBERT CURVE



- Peak Oil – Hubbert predicted declining US reserves after 1975. Declining Global supply after late 2005.
- Hubbert re Conventional.

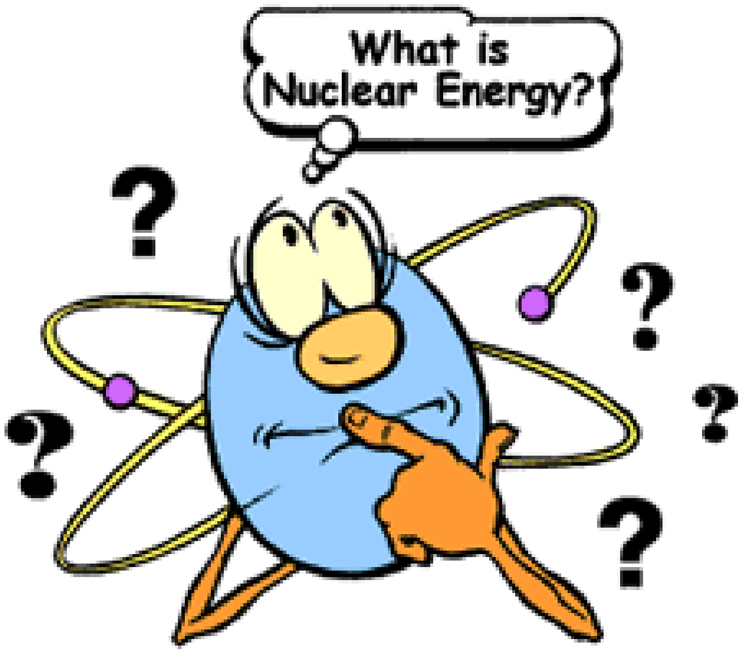
Hubbert (also Deffeyes & Simmons) have been proved right

Kindly supplied by Dr. A. Kaye, Altech Engineering, Inc., Edmonton, Alberta, Canada



Source: IAEA 2000

What is Nuclear Power?



- Conversion of mass into energy, by:
- Release of energy locked up in unstable, heavy atoms (Fission).
- Release of energy by nuclear synthesis (Fusion, emulating the stars).
- Huge resource – enough energy to power the world for millions of years (if we last that long!).

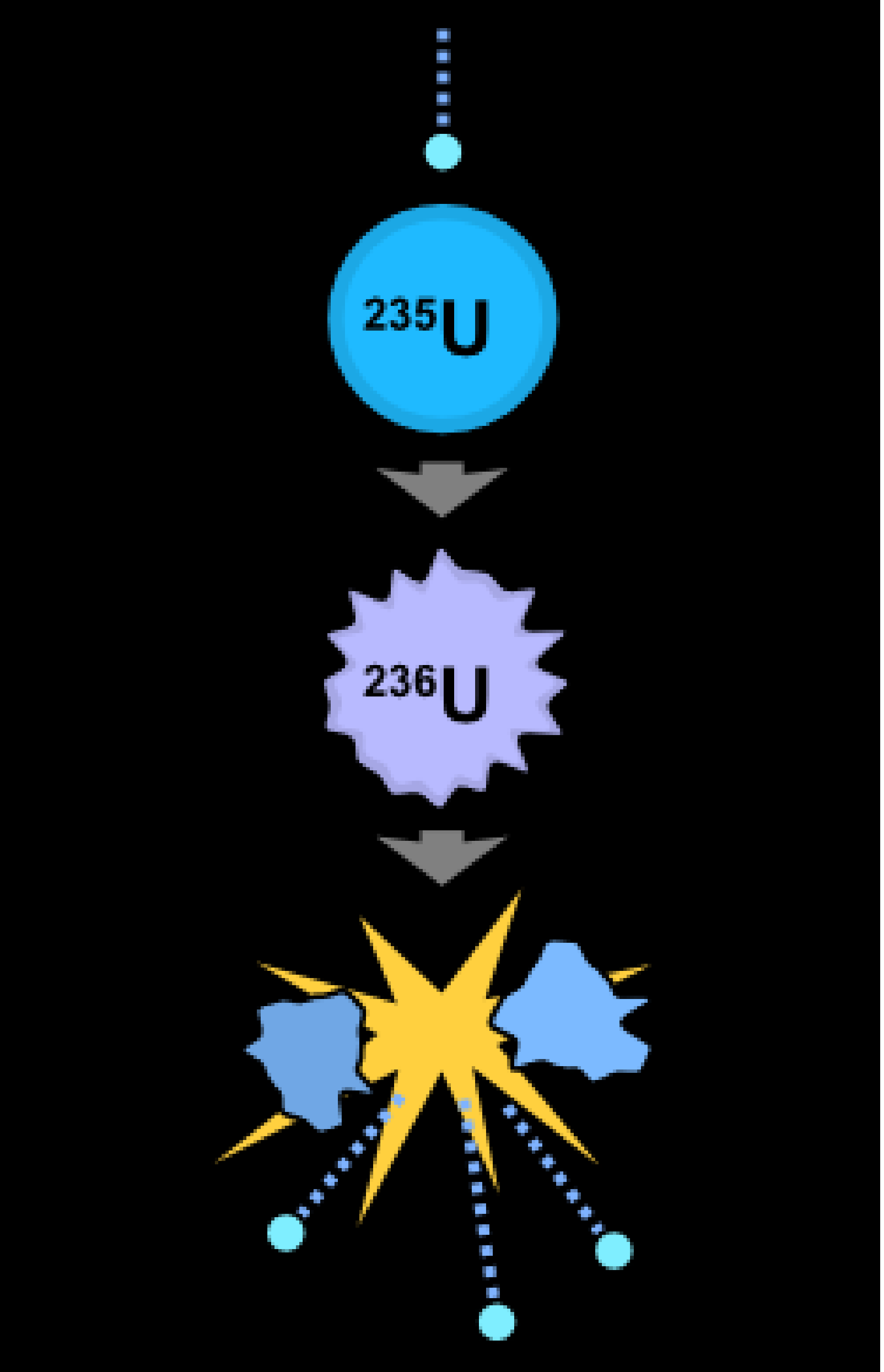
- What processes can be made to convert mass into energy?
- With what efficiency?

Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 1 H																	1 2 He
2 3 Li	2 4 Be											2 5 B	2 6 C	2 7 N	2 8 O	2 9 F	2 10 Ne
3 11 Na	3 12 Mg											3 13 Al	3 14 Si	3 15 P	3 16 S	3 17 Cl	3 18 Ar
4 19 K	4 20 Ca	4 21 Sc	4 22 Ti	4 23 V	4 24 Cr	4 25 Mn	4 26 Fe	4 27 Co	4 28 Ni	4 29 Cu	4 30 Zn	4 31 Ga	4 32 Ge	4 33 As	4 34 Se	4 35 Br	4 36 Kr
5 37 Rb	5 38 Sr	5 39 Y	5 40 Zr	5 41 Nb	5 42 Mo	5 43 Tc	5 44 Ru	5 45 Rh	5 46 Pd	5 47 Ag	5 48 Cd	5 49 In	5 50 Sn	5 51 Sb	5 52 Te	5 53 I	5 54 Xe
6 55 Cs	6 56 Ba	*	6 72 Hf	6 73 Ta	6 74 W	6 75 Re	6 76 Os	6 77 Ir	6 78 Pt	6 79 Au	6 80 Hg	6 81 Tl	6 82 Pb	6 83 Bi	6 84 Po	6 85 At	6 86 Rn
7 87 Fr	7 88 Ra	**	7 104 Rf	7 105 Db	7 106 Sg	7 107 Bh	7 108 Hs	7 109 Mt	7 110 Ds	7 111 Rg	7 112 Uub	7 113 Uut	7 114 Uuq	7 115 Uup	7 116 –	7 117 –	7 118 –
		*	6 57 La	6 58 Ce	6 59 Pr	6 60 Nd	6 61 Pm	6 62 Sm	6 63 Eu	6 64 Gd	6 65 Tb	6 66 Dy	6 67 Ho	6 68 Er	6 69 Tm	6 70 Yb	6 71 Lu
		**	7 89 Ac	7 90 Th	7 91 Pa	7 92 U	7 93 Np	7 94 Pu	7 95 Am	7 96 Cm	7 97 Bk	7 98 Cf	7 99 Es	7 100 Fm	7 101 Md	7 102 No	7 103 Lr

A Brief Primer on Nuclear Fission

- Discovery of the neutron by Chadwick (1936, UK)
- Fissioning of uranium by $^{1}n_{0}$ by Meitner, Hahn and Strassmann in Germany in 1939.
- Bohr - only the rare isotope $^{235}U_{92}$ (0.7% nat. abundance), and not the more plentiful isotope $^{238}U_{92}$ (99.3%), underwent fission by neutron bombardment.
- $^{235}U_{92}$ - can be fissioned by thermal (slow, walking speed) neutrons or by fast neutrons. Probability of each is measured by the fission cross section (σ) in units of Barnes (1 B $=10^{-24}$ cm^2, essentially the area of a nucleus). For $^{235}U_{92}$, σ = 1000 B and 5-8 B for thermal (E ~ 40 meV) and fast (E > 10 MeV) neutrons, respectively.
- Possible to sustain a chain reaction in natural uranium containing only 0.7% $^{235}U_{92}$, if the moderation ("slowing down" or "thermalizing" the energy) of the neutrons is very efficient (Heisenberg 1944). Good moderators are very pure graphite, heavy water (D_2O, the best), and light water (poor compared with D_2O). CANDU reactors uses D_2O as the moderator - no need for enriched fuel. Light water (H_2O) reactors - poorer moderator properties of H_2O compared with D_2O requires that the fuel be enriched to increase the number density of $^{235}U_{92}$ "targets". The fuel is commonly enriched to 2.5 - 3%
- Fast reactors, in which little moderation of the neutrons occurs, like atom bombs, require highly enriched fuel to operate (commonly > 40% $^{235}U_{92}$) At the extreme of this spectrum, an atom bomb requires "bomb grade" fuel of > 96% $^{235}U_{92}$ and a few other attributes that a reactor does not have and which result in an explosion.

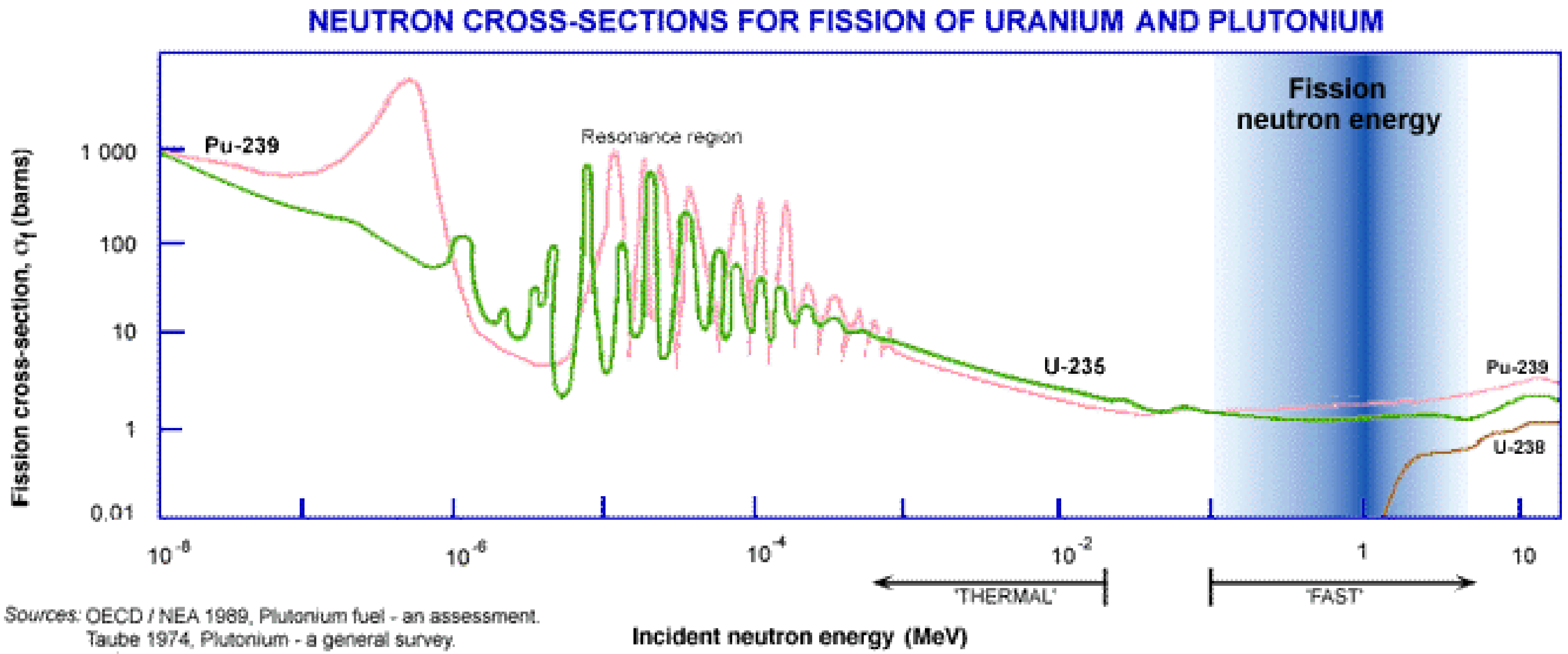


- If the neutron energy is high enough, almost any nucleus can be fissioned. Thus, in a nuclear bomb, a significant fraction of the energy comes from the fissioning of $^{238}U_{92}$ tamper (shell of natural or depleted uranium around the $^{239}Pu_{94}$ "pit"). Likewise, in a fast (neutron) reactor, transuranic elements, such as Am and Cm, are fissioned ("transmuted") to produce a benign waste – hence the name "actinide burner".

- Note that each fission produces 2-3 neutrons that can then fission other "fertile" atoms, such as $^{235}U_{92}$, $^{239}Pu_{94}$, and $^{232}Th_{90}$ to produce a chain reaction. 1, 2, 4, 8, ….2^n, where n is the number of generations.

- Some neutrons may be captured by non-fertile atoms (e.g., $^{238}U_{92}$ to produce other elements. If the capture cross section is sufficiently high (e.g., $^{10}B_5$) the elements act as "poisons" and may stop the chain reaction.

- Poisoning by fission products eventually limits the "burn-up" of the fuel.



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28}m2, 1 MeV = 1.6×10^{-13}J

Neutron Capture

The capture cross section for fast neutrons by $^{238}U_{92}$ is not zero, so that the following occur:

$$^{1}n_{0} + {}^{238}U_{92} \rightarrow {}^{239}U_{92}^{*}$$

$$^{239}U_{92}^{*} \rightarrow {}^{239}Np_{93} + e^{-} \text{ (}\beta\text{ particle)}$$

$$^{239}Np_{93} \rightarrow {}^{239}Pu_{94} + e^{-} \text{ (}\beta\text{ particle)}$$

But, we also have

$$^{1}n_{0} + {}^{239}Pu_{94} \rightarrow {}^{240}Pu_{94} \text{ (non-fissile by thermal neutrons)}$$

$$^{1}n_{0} + {}^{240}Pu_{94} \rightarrow {}^{241}Pu_{94} \text{ (spontaneously fissile)}$$

etc

If the neutron economy can be arranged such that the rate of production of $^{239}Pu_{94}$ exceeds the rate of consumption of $^{235}U_{92}$, and since $^{239}Pu_{94}$ is fissile to neutrons, the reactor produces more fuel than it consumes – thus it is a "breeder reactor". It is estimated that about 40% of the power in a PWR at the end of a cycle is produced by fissioning plutonium.

Mass/Energy Duality

All energy generation arises from the conversion of mass. In 1905, Albert Einstein:

$$E = mc^2$$

$c = 3x10^8$ m/s. Therefore, 1 gram of mass ≡ $9x10^{13}$ J. That's a lot of energy!!! But, how much is it exactly?

- Noting that 1W = 1J/s, the conversion of 1g/s of mass corresponds to the generation of $9x10^{13}$ W or $9x10^7$MW. A large nuclear power plant is 1000 MWe or 3000MWt, so that it would take 30,000 such plants to destroy 1 g/s. Or, from another perspective, a typical plant converts about 33μg/s or 1 kg/year of mass into energy.

- Energy generation technologies may be differentiated by their mass conversion efficiencies, as indicated next.

Mass Conversion Efficiencies

Fuel	Energy (kW.hr)	Converted Mass (µg)	% Conversion
1 bbl. oil	576	23	$1.64x10^{-8}$
1 ton coal	2,297	92	$0.92x10^{-8}$
100 ft^3 CH_4	12	0.48	$2.37x10^{-8}$
1g $^{235}U_{92}$		929	0.093
$^2D_1$+$^3T_1$		0.019428u	0.38

Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics

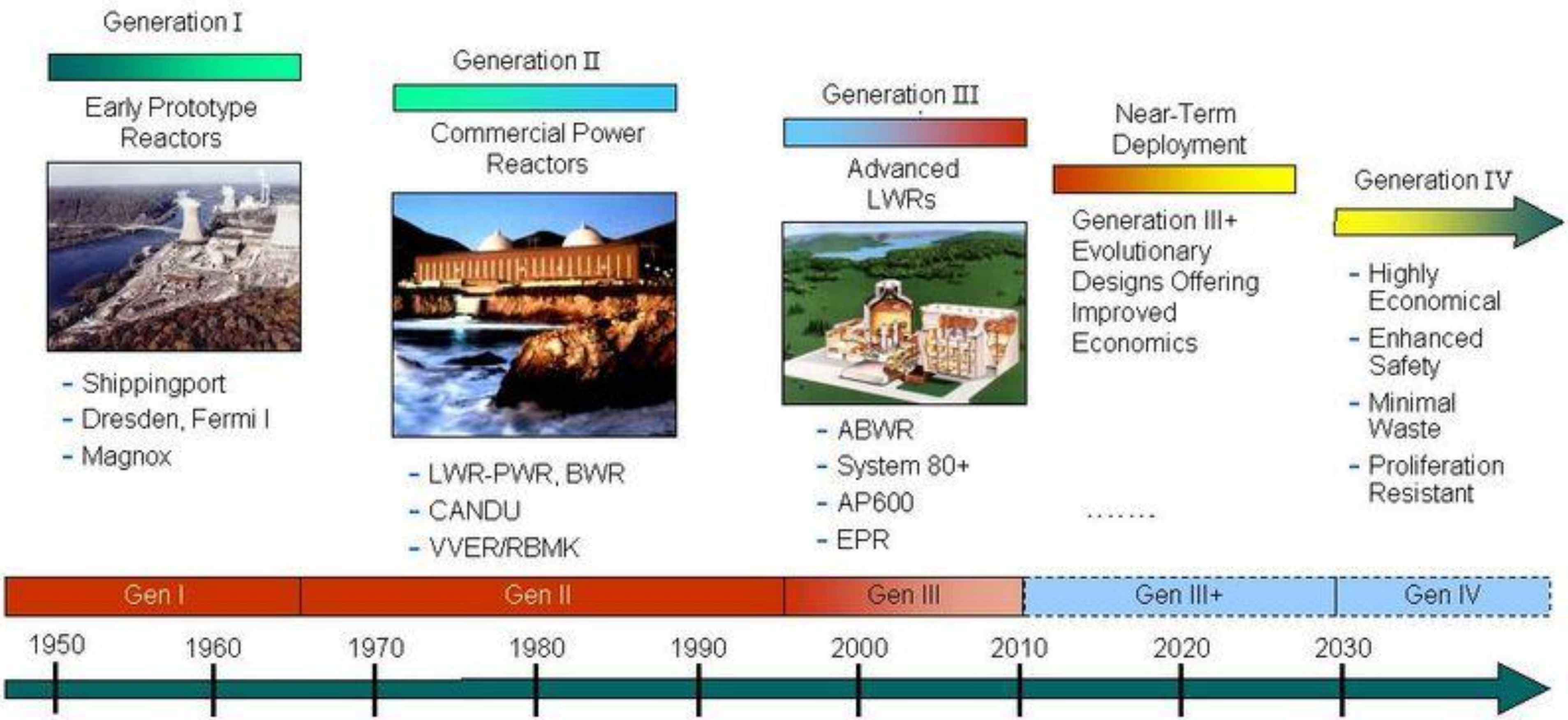


TABLE 5: Nuclear power plants in commercial operation

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized Water Reactor (PWR)	US, France, Japan, Russia, China, Korea, UK, South Africa	252	235	Slightly enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden, Spain, Switzerland, Taiwan	93	83	Slightly enriched UO_2	water	water
Gas-cooled Reactor (Magnox & AGR)	UK	34	13	natural U (metal), enriched UO_2	CO_2	graphite
Pressurized Heavy Water Reactor "CANDU" (PHWR)	Canada, Romania, Korea, India	33	18	natural UO_2	heavy water	heavy water
Light Water Cooled Graphite Reactor (RBMK)	Russia	14	14	Slightly enriched UO_2	water	graphite
Fast Neutron Breeder Reactor (FNBR)	Japan, France, Russia	4	1.3	Highly enriched PuO_2 and UO_2	liquid sodium	none
other	Russia, Japan	5	0.2			
	TOTAL	**435**	**364**			

Source: Nuclear Engineering International handbook 2000.

Some fatalities in energy related activities

Place	year	number killed	comments
Machhu II, India	1979	2500	hydro-electric dam failure
Hirakud, India	1980	1000	hydro-electric dam failure
Ortuella, Spain	1980	70	gas explosion
Donbass, Ukraine	1980	68	coal mine methane explosion
Israel	1982	89	gas explosion
Guavio, Colombia	1983	160	hydro-electric dam failure
Nile R, Egypt	1983	317	LPG explosion
Cubatao, Brazil	1984	508	oil fire
Mexico City	1984	498	LPG explosion
Tbilisi, Russia	1984	100	gas explosion
northern Taiwan	1984	314	3 coal mine accidents
Chernobyl, Ukraine	1986	31+	nuclear reactor accident
Piper Alpha, North Sea	1988	167	explosion of offshore oil platform
Asha-ufa, Siberia	1989	600	LPG pipeline leak and fire
Dobrnja, Yugoslavia	1990	178	coal mine
Hongton, Shanxi, China	1991	147	coal mine
Belci, Romania	1991	116	hydro-electric dam failure
Kozlu, Turkey	1992	272	coal mine methane explosion
Cuenca, Equador	1993	200	coal mine
Durunkha, Egypt	1994	580	fuel depot hit by lightning

Taegu, S.Korea	1995	100	oil & gas explosion
Spitsbergen, Russia	1996	141	coal mine
Henan, China	1996	84	coal mine methane explosion
Datong, China	1996	114	coal mine methane explosion
Henan, China	1997	89	coal mine methane explosion
Fushun, China	1997	68	coal mine methane explosion
Kuzbass, Siberia	1997	67	coal mine methane explosion
Huainan, China	1997	89	coal mine methane explosion
Huainan, China	1997	45	coal mine methane explosion
Guizhou, China	1997	43	coal mine methane explosion
Donbass, Ukraine	1998	63	coal mine methane explosion
Liaoning, China	1998	71	coal mine methane explosion
Warri, Nigeria	1998	500+	oil pipeline leak and fire
Donbass, Ukraine	1999	50+	coal mine methane explosion
Donbass, Ukraine	2000	80	coal mine methane explosion
Shanxi, China	2000	40	coal mine methane explosion
Guizhou, China	2000	150	coal mine methane explosion
Shanxi, China	2001	38	coal mine methane explosion

LPG and oil accidents with less than 300 fatalities, and coal mine accidents with less than 100 fatalities are generally not shown unless recent. Deaths per million tons of coal mined range from 0.1 per year in Australia and USA to 119 in Turkey to even more in other countries. China's total death toll from coal mining averages well over 1000 per year (reportedly 5300 in 2000); Ukraine's is over two hundred per year (eg. 1999: 274, 1998: 360, 1995: 339, 1992: 459).

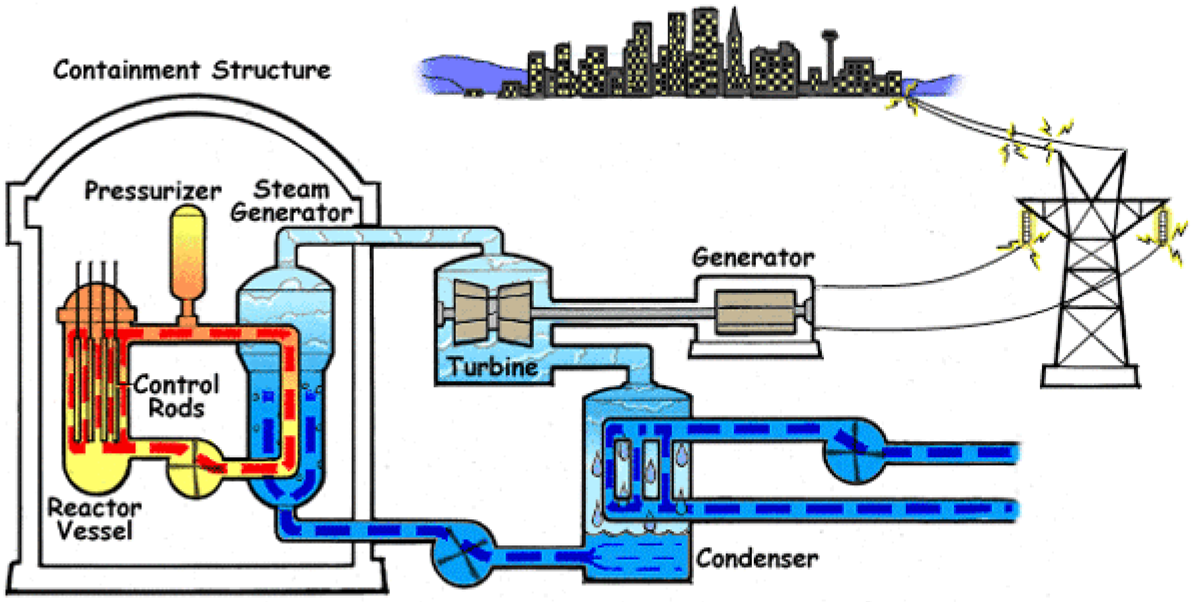
Serious Reactor Accidents

Serious accidents in military, research and commercial reactors. All except Browns Ferry and Vandellos involved damage to or malfunction of the reactor core. At Browns Ferry a fire damaged control cables and resulted in an 18-month shutdown for repairs, at Vandellos a turbine fire made the 17 year old plant uneconomic to repair.

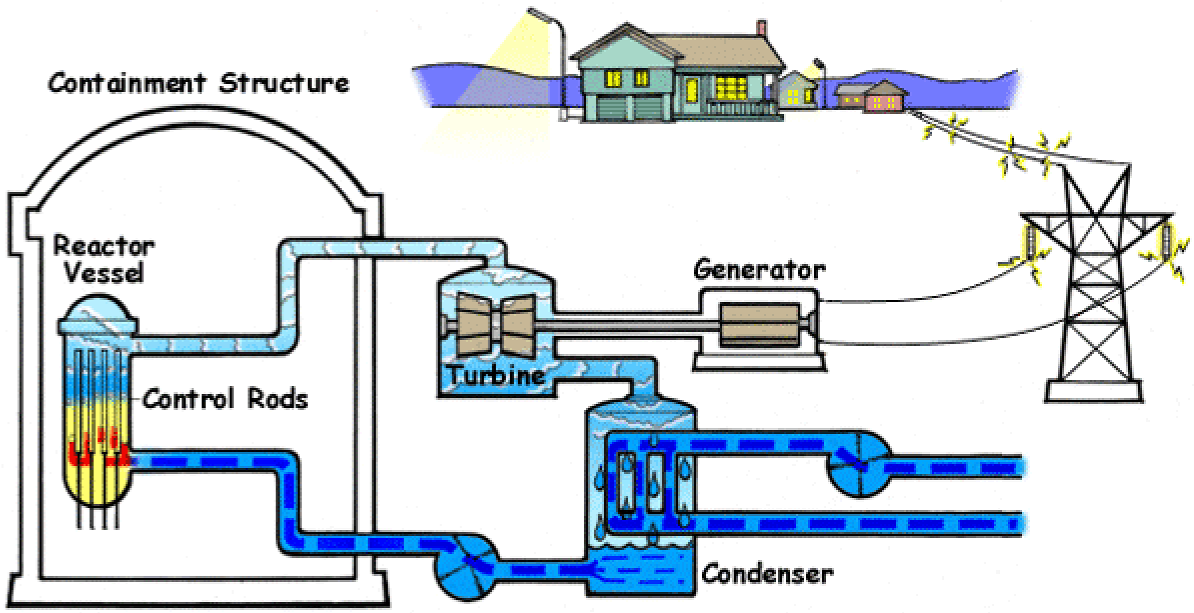
Reactor	Date	Immediate Deaths	Environmental effect	Follow-up action
NRX, Canada (experimental, 40 MWt)	1952	Nil	Nil	Repaired (new core) closed 1992
Windscale-1, UK (military plutonium-producing pile)	1957	Nil	Widespread contamination. Farms affected (c 1.5 x 10^{15} Bq released)	Entombed (filled with concrete) Being demolished.
SL-1, USA (experimental, military, 3 MWt)	1961	Three operators	Very minor radioactive release	Decommissioned
Fermi-1 USA (experimental breeder, 66 MWe)	1966	Nil	Nil	Repaired, restarted 1972

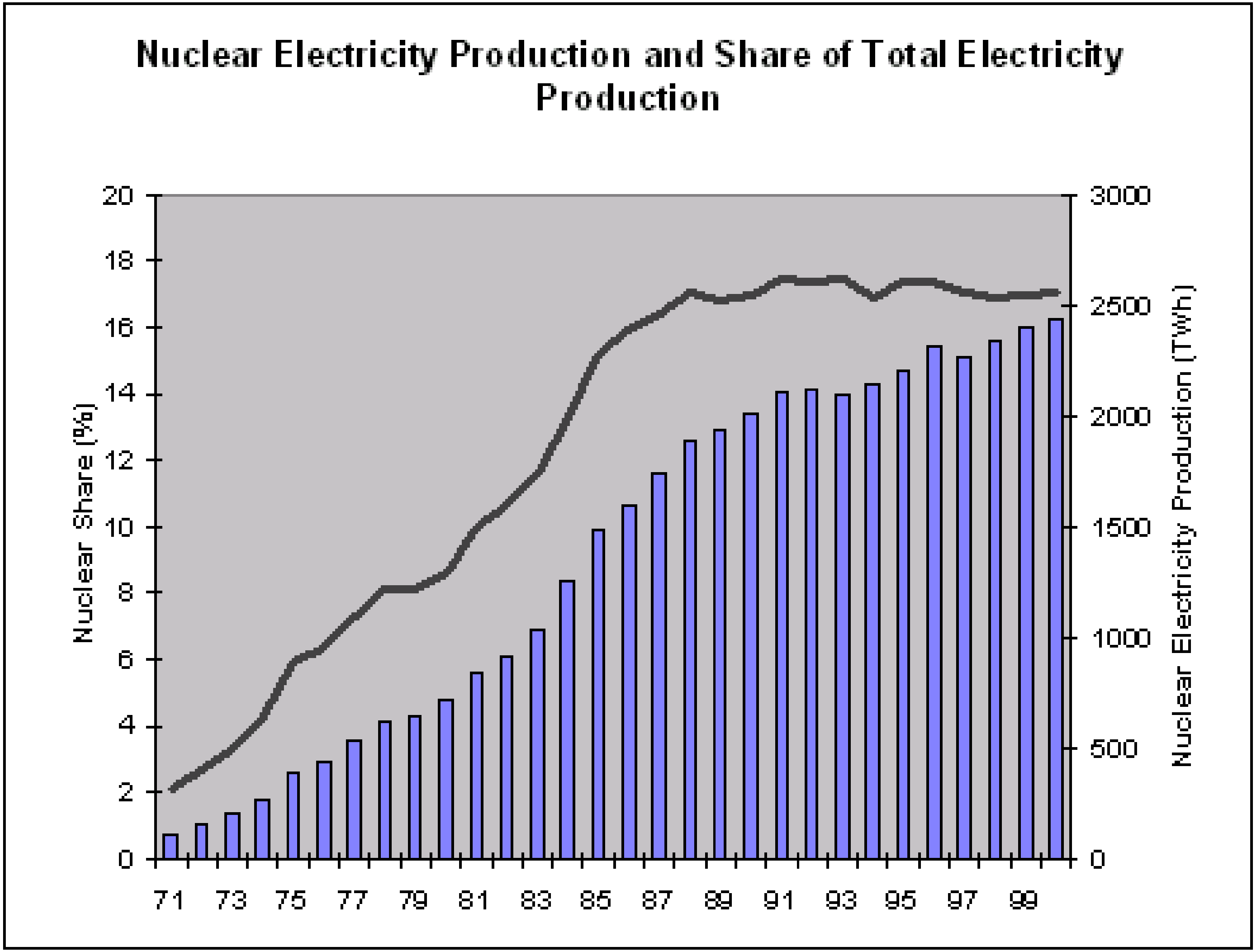
Lucens, Switzerland (experimental, 7.5 MWe)	1969	Nil	Very minor radioactive release	Decommissioned
Browns Ferry, USA (commercial, 2 x 1080 MWe)	1975	Nil	Nil	Repaired
Three-Mile Island-2, USA (commercial, 880 MWe)	1979	Nil	Minor short-term radiation dose (within ICRP limits) to public, delayed release of 2 x 10^{14} Bq of Kr-85	Clean-up program complete, in monitored storage stage of decommissioning
Saint Laurent-A2, France (commercial, 450 MWe)	1980	Nil	Minor radiation release (8 x 10^{10} Bq)	Repaired, (Decomm. 1992)
Chernobyl-4, Ukraine (commercial, 950 MWe)	1986	31 staff and firefighters	Major radiation release across E.Europe and Scandinavia (11 x 10^{18} Bq)	Entombed
Vandellos-1, Spain (commercial, 480 MWe)	1989	Nil	Nil	Decommissioned
Fukushima-Daiichi, 6 BWRs, 4.7 GWe. Total.	March 11, 2011	Nil	Possibly substantial	Currently being stabilized.

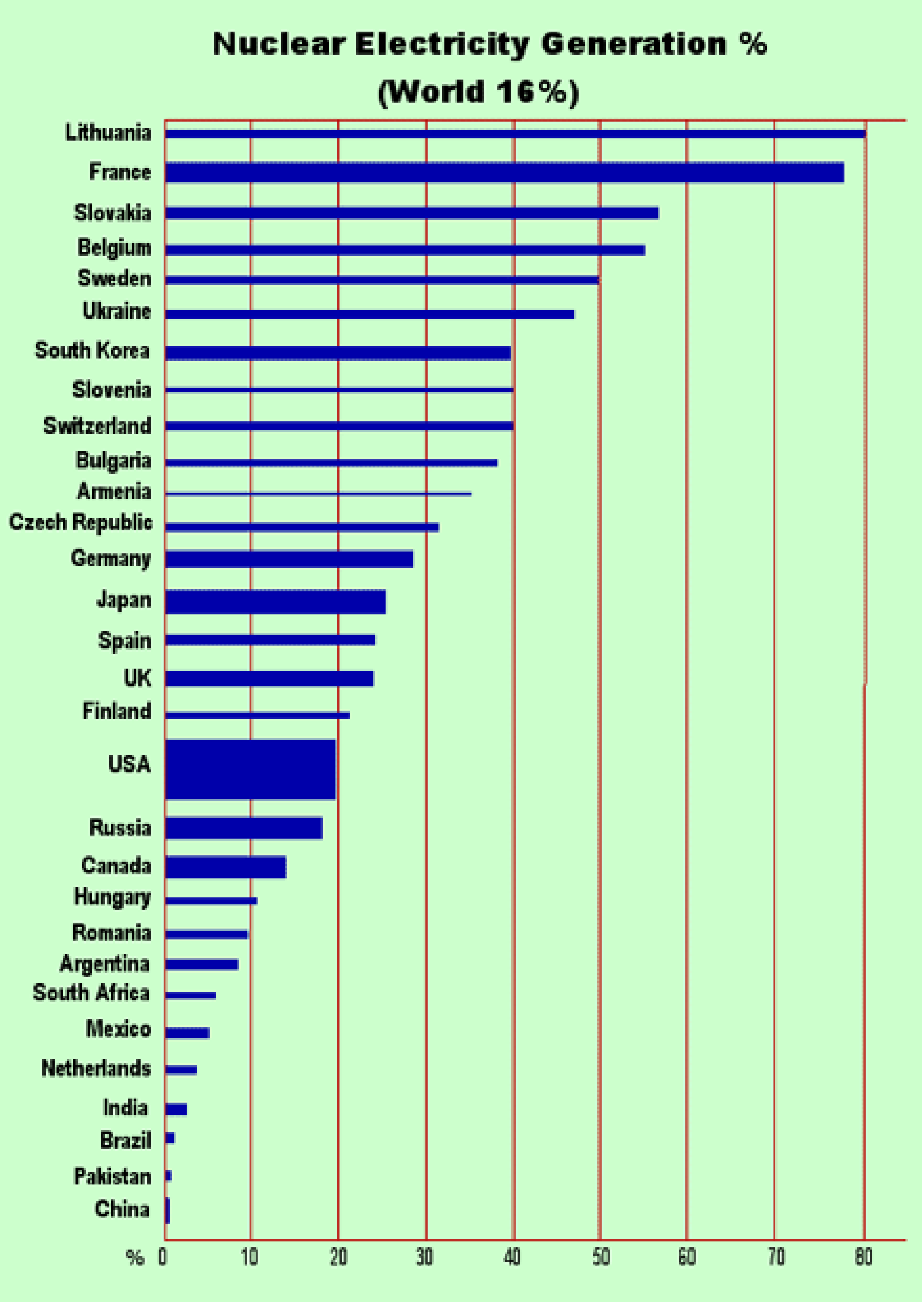
Pressurized Water Reactor (PWR)



Boiling Water Reactor (BWR)

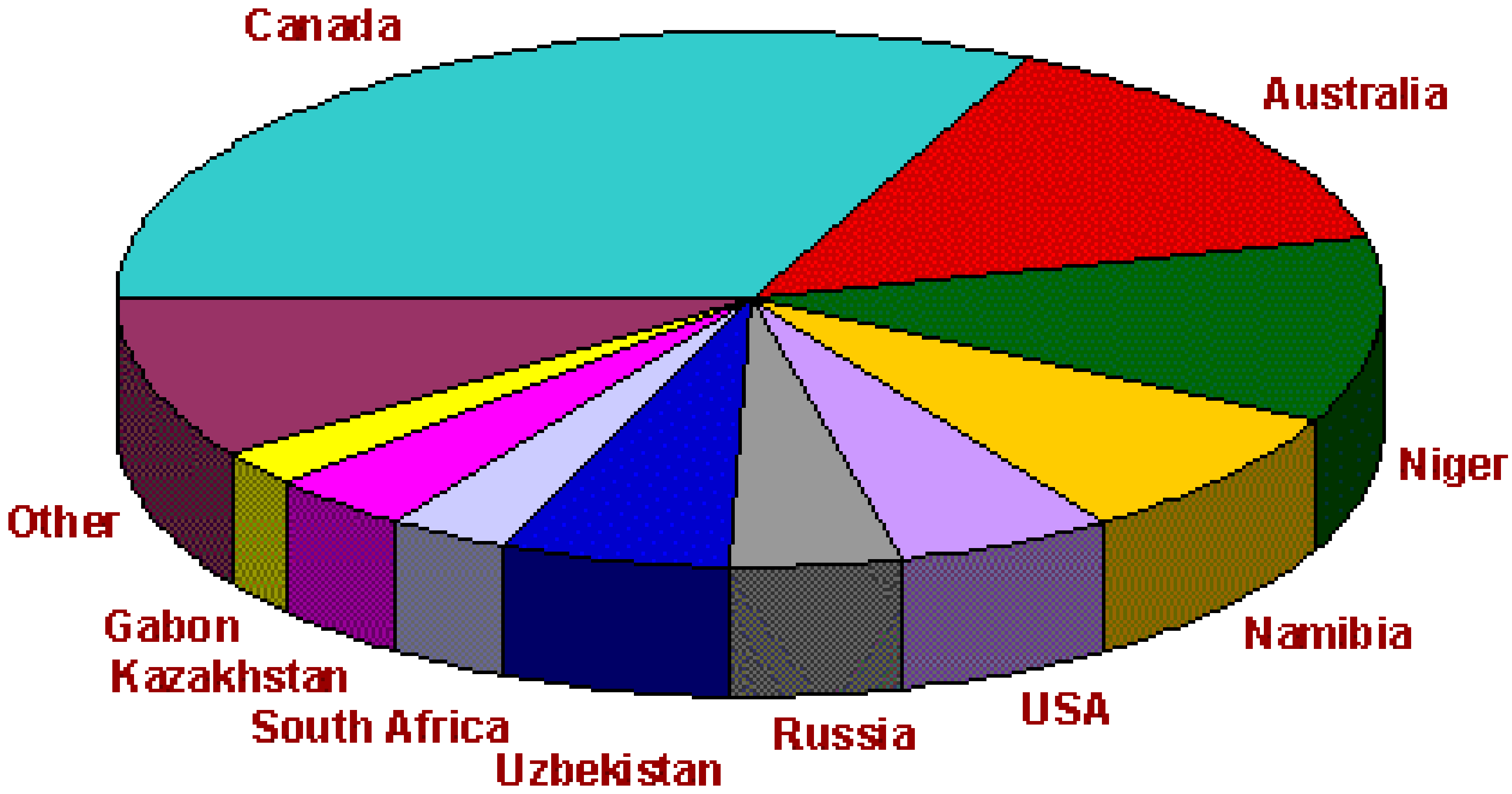



Nuclear Electricity Production and Share of Total Electricity Production
Nuclear Share (%)
Nuclear Electricity Production (TWh)
0
2
4
6
8
10
12
14
16
18
20
0
500
1000
1500
2000
2500
3000
71
73
75
77
79
81
83
85
87
89
91
93
95
97
99

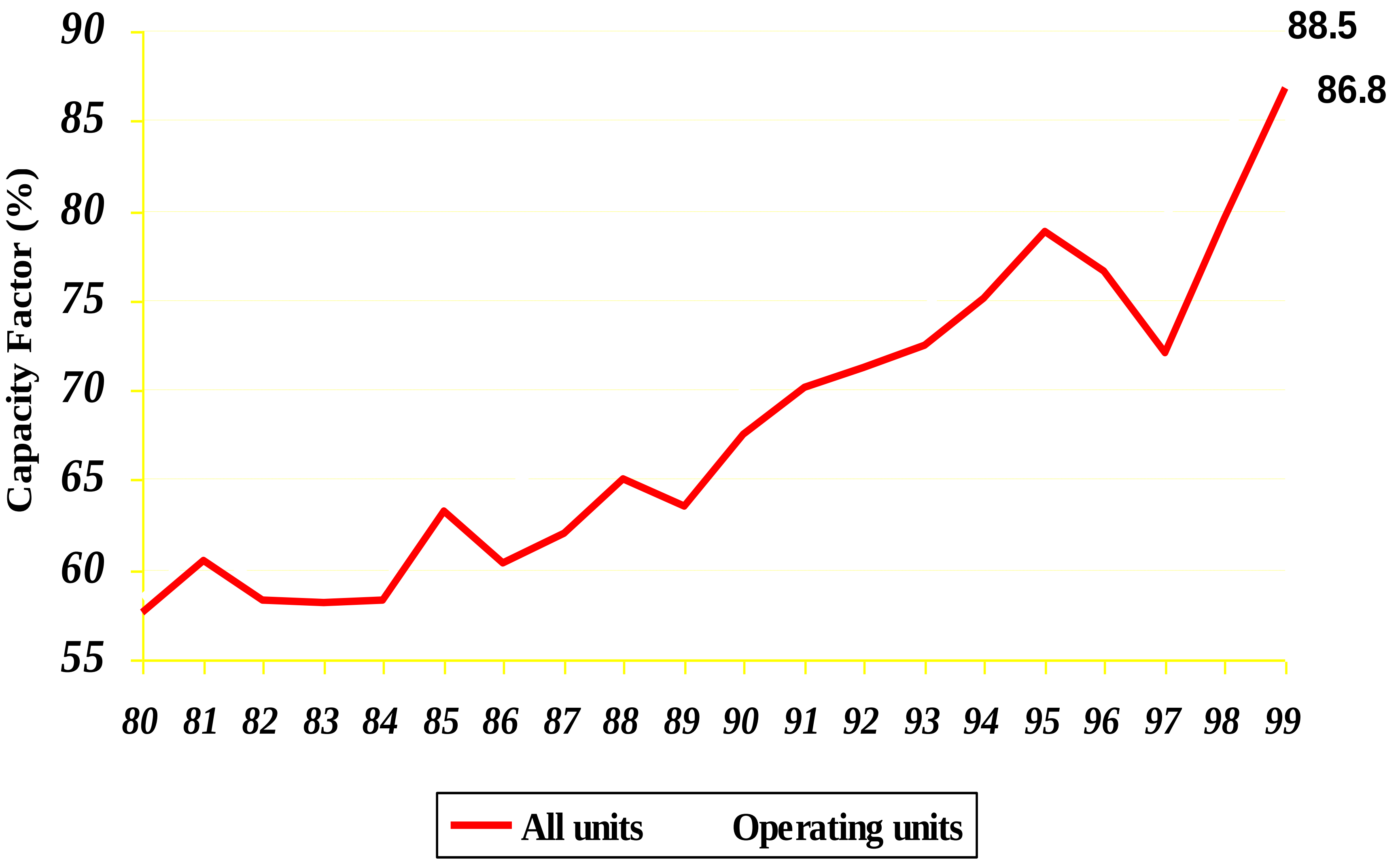


Nuclear Electricity Generation %
(World 16%)
Lithuania
France
Slovakia
Belgium
Sweden
Ukraine
South Korea
Slovenia
Switzerland
Bulgaria
Armenia
Czech Republic
Germany
Japan
Spain
UK
Finland
USA
Russia
Canada
Hungary
Romania
Argentina
South Africa
Mexico
Netherlands
India
Brazil
Pakistan
China
%
0
10
20
30
40
50
60
70
80

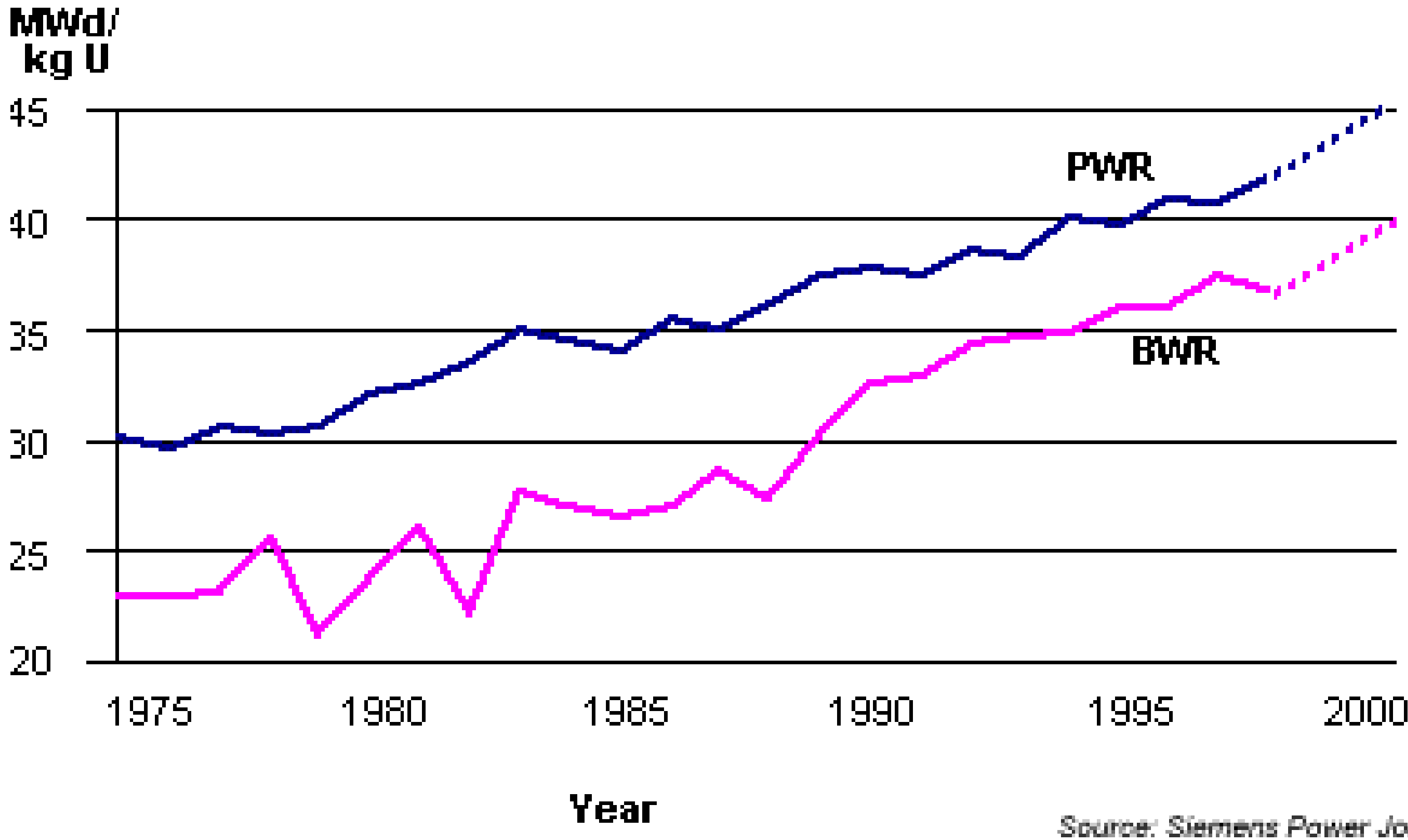
World U Production, 1998



US Nuclear Industry Is Achieving Record Levels of Performance (1980-1999)



World-wide trend of fuel burn-up



Source: Siemens Power Journal 4/99

Generation III Advanced Reactors

Advanced Reactor Designs
-standardised designs with passive safety systems

GE-Hitachi-Toshiba **ABWR**	1300 MWe BWR	Japan & USA
ABB-CE **System 80+**	1300 MWe PWR	USA
Westinghouse **AP 500**	600 MWe BWR	USA
AECL **CANDU-9**	92 -1300 MWe HWR	Canada
OKBM **V-407 (VVER)**	640 MWe PWR	Russia
OKBM **V-392 (VVER)**	1000 MWe PWR	Russia
Siemens et al **EPR**	1525-1800 MWe PWR	France & Germany
GA-Minatom **GTMHR**	modules of 250 MWe HTGR	US-Russia-Fr-Jp

EVOLUTIONARY: Four advanced boiling-water reactors, such as this one at the Lungmen Power Station, Taiwan, are under construction in Japan and Taiwan. TAIWAN POWER COMPANY PHOTO

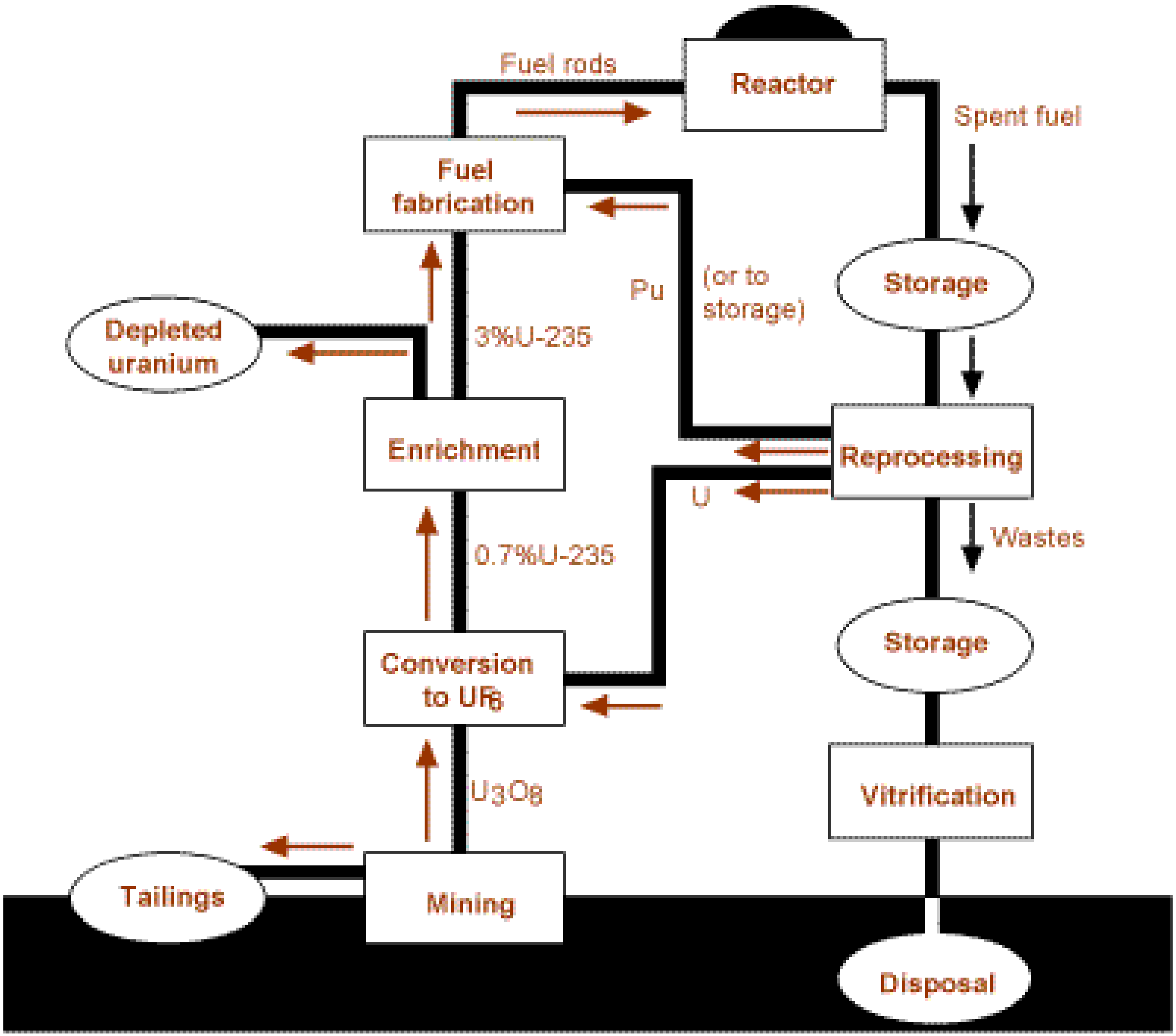
Generation IV Fast Neutron Reactors

Concept	**Moderator**	**Coolant**	**Operating Temperature**	**Capabilities/Features**
Gas Cooled Fast Reactor	None (fast neutron spectrum)	Helium	850°C	• Actinide burner • Pu breeding • Ceramic fuel
Lead Cooled Fast Reactor	None (fast neutron spectrum)	Liquid lead	550 – 800°C	Actinide burner Pu breeding U/Pu metallic fuel SS cladding
Sodium Cooled fast Reactor	None (fast neutron spectrum)	Liquid sodium	550 – 800°C	• Actinide burner • Pu breeding • U/Pu metallic fuel • SS cladding

Generation IV Thermal Neutron Reactors

Concept	Moderator	Coolant	Operating Temperature	Capabilities
Molten Salt Reactor	Graphite (thermal neutron spectrum)	Helium	850°C	•Actinide burner •Pu breeding •Homogeneous fuel
Supercritical Water Reactor	Light water (thermal neutron spectrum)	Water	500 -600°C	•Actinide burner •Pu breeding •Very high thermal efficiency
Very High Temperature Reactor	Graphite (thermal neutron spectrum)	Helium	1000°C	•Actinide burner •Pu breeding •Hydrogen production

The Closed Fuel Cycle



FUSION

- Thermo-nuclear synthesis of higher elements from the light elements (e.g., helium from the isotopes of hydrogen).
- Process occurs in the stars, including our sun.
- Relies on bringing together nuclei that are subjected to Columbic repulsion. Requires very high temperatures and hence kinetic energies to overcome the repulsion.
- Promises virtually unlimited energy supply.
- Feasibility technically proven – thermonuclear weapons, JET, ITER.
- Isotopes of hydrogen; ${}^{2}D_{1}$ (deuterium), ${}^{3}T_{1}$(tritium). Minimal inter-nuclear repulsion.
- Results in much greater conversion of mass into energy than does fission.
- Minimal waste (some neutron activation of structural materials).
- Two basic strategies: Plasma inertial confinement (emulates the stars) and laser implosion (emulates thermonuclear weapons). Both have enjoyed some success, but practical devises are still many decades away.

Thermonuclear Reactions

Reaction	**Reaction Equation**	**Initial Mass (u)**	**Mass Change (u)**	**% Mass Change**
D-D	${}^{2}D_{1} + {}^{2}D_{1} \rightarrow {}^{3}He_{2} + {}^{1}n_{0}$	4.027106424	-2.44152×10^{-3}	0.06062
D-D	${}^{2}D_{1} + {}^{2}D_{1} \rightarrow {}^{3}H_{1} + {}^{1}p_{1}$	4.027106424	-3.780754×10^{-3}	0.09388
D-T	${}^{2}D_{1} + {}^{3}T_{1} \rightarrow {}^{4}He_{2} + {}^{1}n_{0}$	5.029602412	-0.019427508	0.3863
e^{-}-p^{+}	$e^{-} + p^{+} \rightarrow 2h\nu$	1.8219×10^{-31}	-1.8219×10^{-31}	100

Must overcome Coulombic repulsion of nuclei in the plasma

Preferred Reaction

- The easiest reaction to achieve is:
  $^{2}D_{1} + {}^{3}T_{1} \rightarrow {}^{4}He_{2} + {}^{1}n_{0}$
- Deuterium occurs naturally while tritium does not
- Tritium must be "bred":
  $^{6}Li_{3} + {}^{1}n_{0} \rightarrow {}^{3}T_{1} + {}^{4}He_{2}$
- Process can be run from just two elements: lithium and deuterium
- Lowest "ignition" temperature.

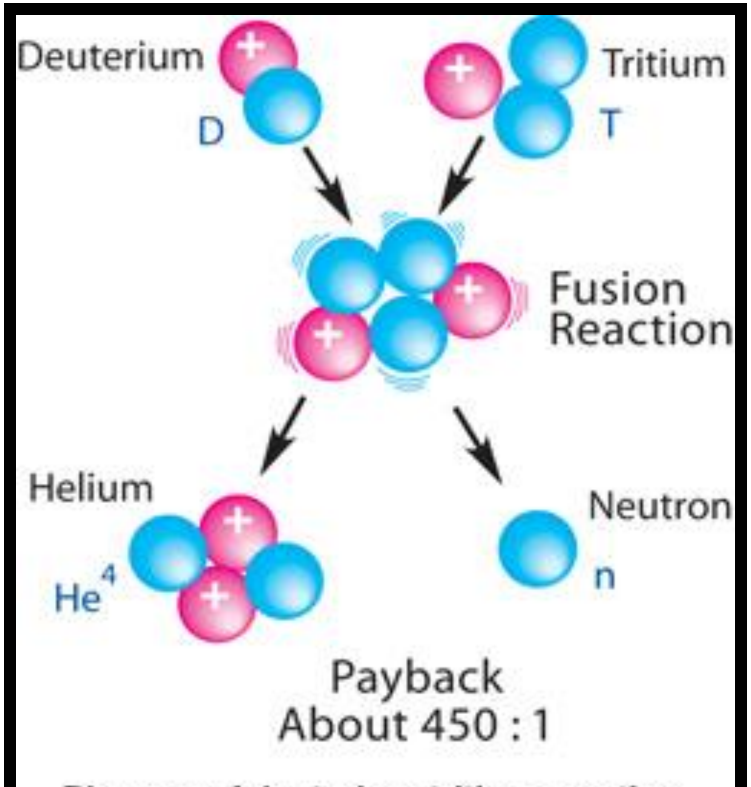
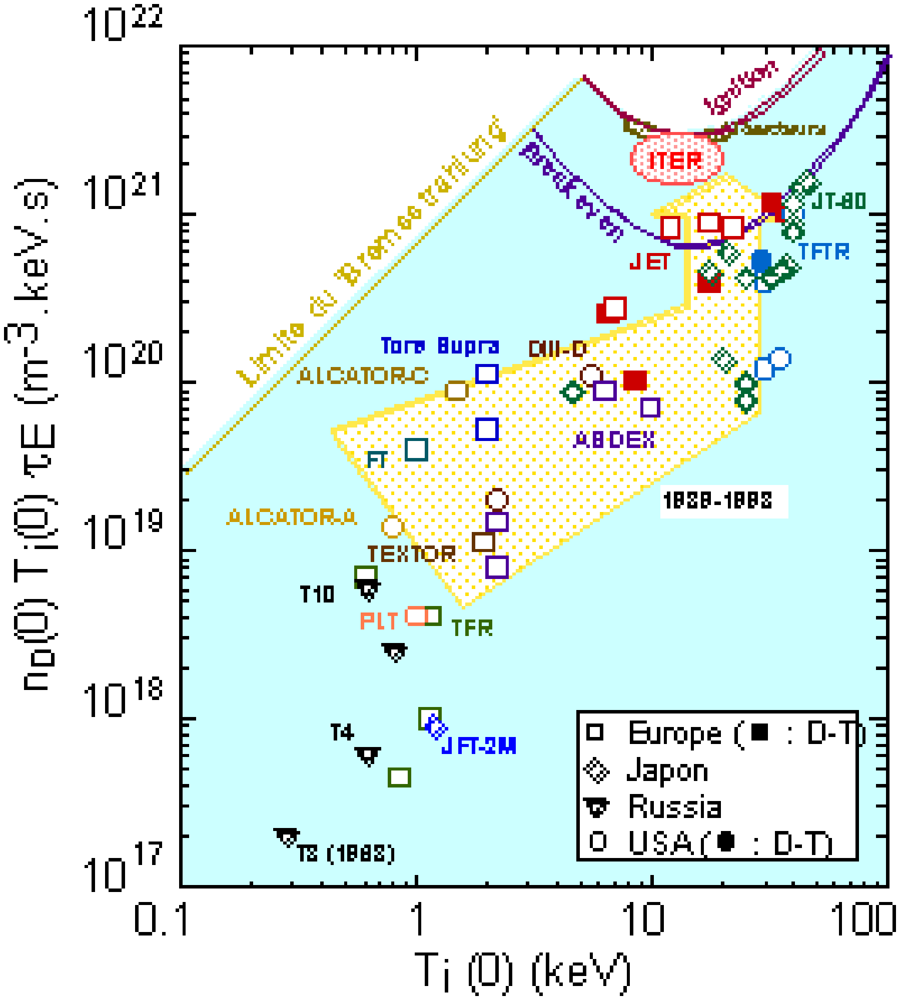


Diagram of deuterium-tritium reaction.

PRINCETON PLASMA PHYSICS LABORATORY. <www.pppl.gov>.

Lawson Energy Balance

Yields the conditions necessary for the generation of power from a confined plasma.



nTτ_E > 10^{21} keV.m^{-3}.s

n = plasma density (m^{-3}).

T = plasma temperature (keV)

τ_E confinement time (s)

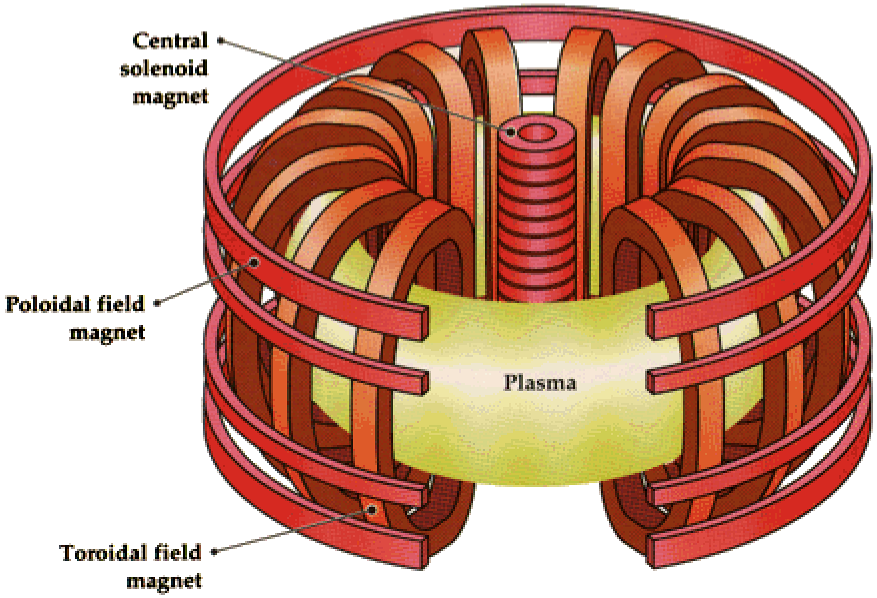
- **Low density, long confinement time – Tokamak**
- **High density, short confinement time – Laser fusion**
- **Q = nTτ_E/Input power > 10 for practical reactor (ITER).**

Containment Methods

- Fusion must be controlled to be useful
- Three major containment categories:
  - Gravitational –Sun & stars
  - Magnetic -- Tokamaks
  - Inertial -- Laser

Tokamak

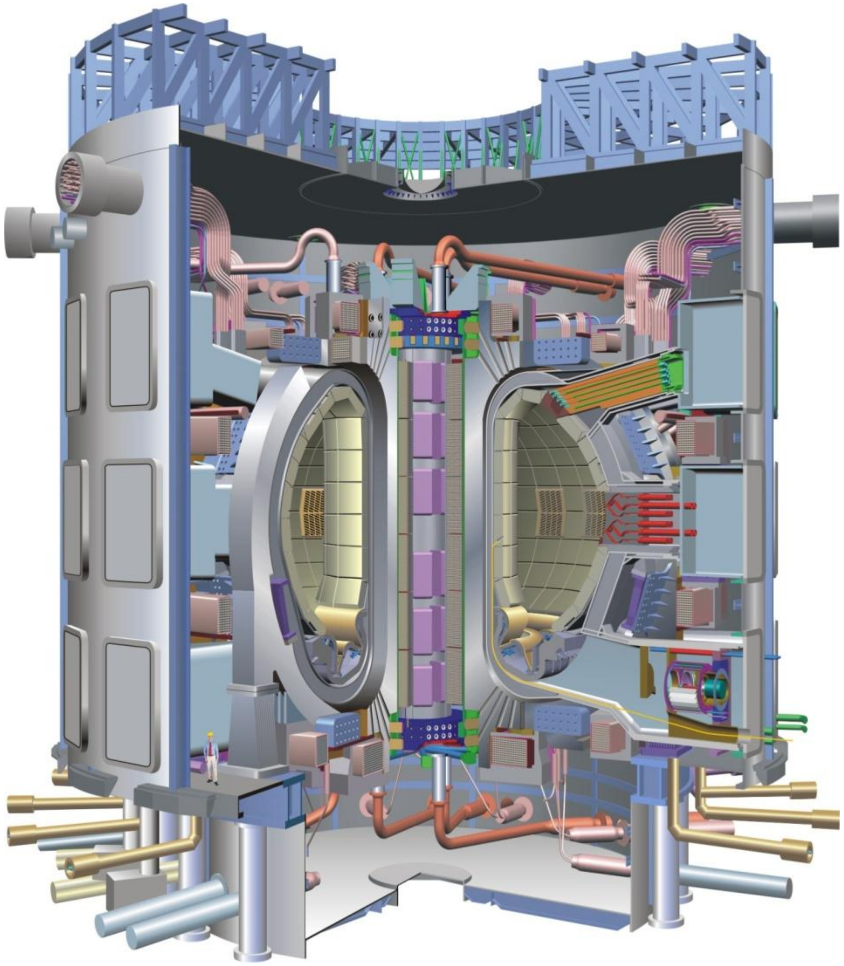
- Uses poloidal and toroidal magnets to control the shape and density of the plasma



<http://library.thinkquest.org/17940/texts/magnetic_confinement/magnetic_confinement.html>

ITER

- Being funded by the international community
- Full scale device
  - Produce 500MW of power
  - 500 second length
- Goal is to prove that fusion power is attainable



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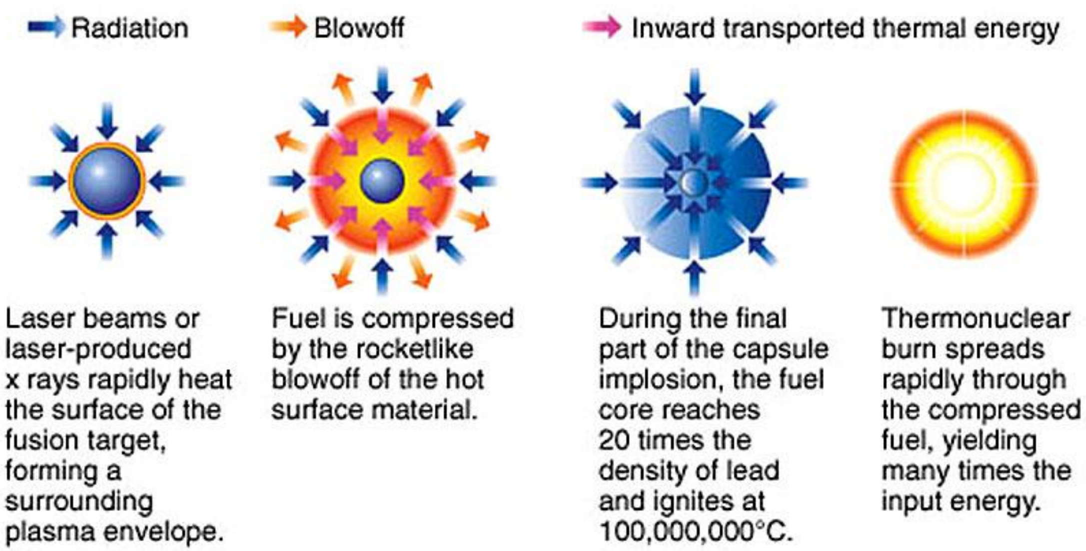
Inertial Confinement

- Uses lasers to heat and compress fuel pellets of deuterium and tritium
- Energy levels become so high they can overcome natural repelling forces and collide
- These collisions create energy and causes the ignition of the rest of the fuel.



<http://en.wikipedia.org/wiki/ICF>

Inertial Confinement Fusion (cont.)

- **Controversial because it is the same technique used in Hydrogen Bombs – radiation compression**
- **National Ignition Facility being built for research in ICF at Lawrence Livermore National Laboratory**
- **Uses 192 laser beams designed to deliver 1.8 million joules of ultraviolet laser energy and 500 terawatts of power to millimeter-sized targets. <http://www.llnl.gov/nif/project/nif_works.html>**

Nuclear vs. Other forms of Energy

- If an average size, 1000 MWe reactor is run at 90 % capacity for one year, 7.9 billion KWh are produced. This is enough to supply electricity to about 740,000 houses. To equal this with other forms of energy, you would need the following amounts of material.

Oil – 13.7 million barrels	1 barrel yields 576 KWh
Coal – 3.4 million short tons	1 ton yields 2,297 KWh
Natural Gas – 65.8 billion cubic feet	100 cubic feet yields 12 KWh
(based on average conversion rates from the Energy Information Administration	

Table from ref. [6]

Coal versus Fusion

1000 MWe Power Plant

	COAL	D-T FUSION
FUEL	9000 T. Coal	1.0 lb. D_2 3.0 lb. Li^6 (1.5 lb. T_2)
WASTE	30,000 T. CO_2 600 T. SO_2 80 T. NO_2 (23.4 lb. U) (57.6 lb. Th)	4.0 lb. He^4