

Sustainability in the technological age

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Presentation can be downloaded:

<http://www.phenix.bnl.gov/WWW/publish/ondrejch/talks/earthweek/>

Many thanks to, among countless others

* **Rod Adams**, <http://atomicinsights.blogspot.com/>

* **Tom Blees**, <http://www.prescriptionfortheplanet.com/>

* **Kirk Sorensen**, <http://energyfromthorium.com>, “Thorium-based Nuclear Power: The Road to Green, Sustainable Nuclear Power”, Green Energy Forum, July 25, 2007),

* **Robert Hargraves**, “Aim High!, Liquid Fluoride Thorium Reactor - Energy cheaper than from coal can solve more crises than just global warming”,

<http://rethinkingnuclearpower.googlepages.com/aimhigh>

* **David LeBlanc**, “Liquid Fluoride Reactors: A New Beginning for an Old Idea”, Google tech talk February 20, 2009, <http://www.youtube.com/watch?v=8F0tUDJ35So>

Selected problems with sustainability

Growing population, poverty and per capita energy needs

Global pollution from combustion

CO₂ – global climate change

SO₂, NO_x, - acid rain, smog, illness

particulate matter – carcinogenic, cardiovascular problems

arsenic, mercury, cadmium, uranium, thorium – toxic metals

Air pollution deaths – 3M deaths annually, ½ outdoor, ½ indoor (fires)

http://en.wikipedia.org/wiki/Asian_brown_cloud

Resources – drinkable water, arable land, raw materials

Sustainability of energy resources

Nuclear energy – contemporary = best option at hand

Closed cycles (U, Th) = sustainable alternatives

Talk outline

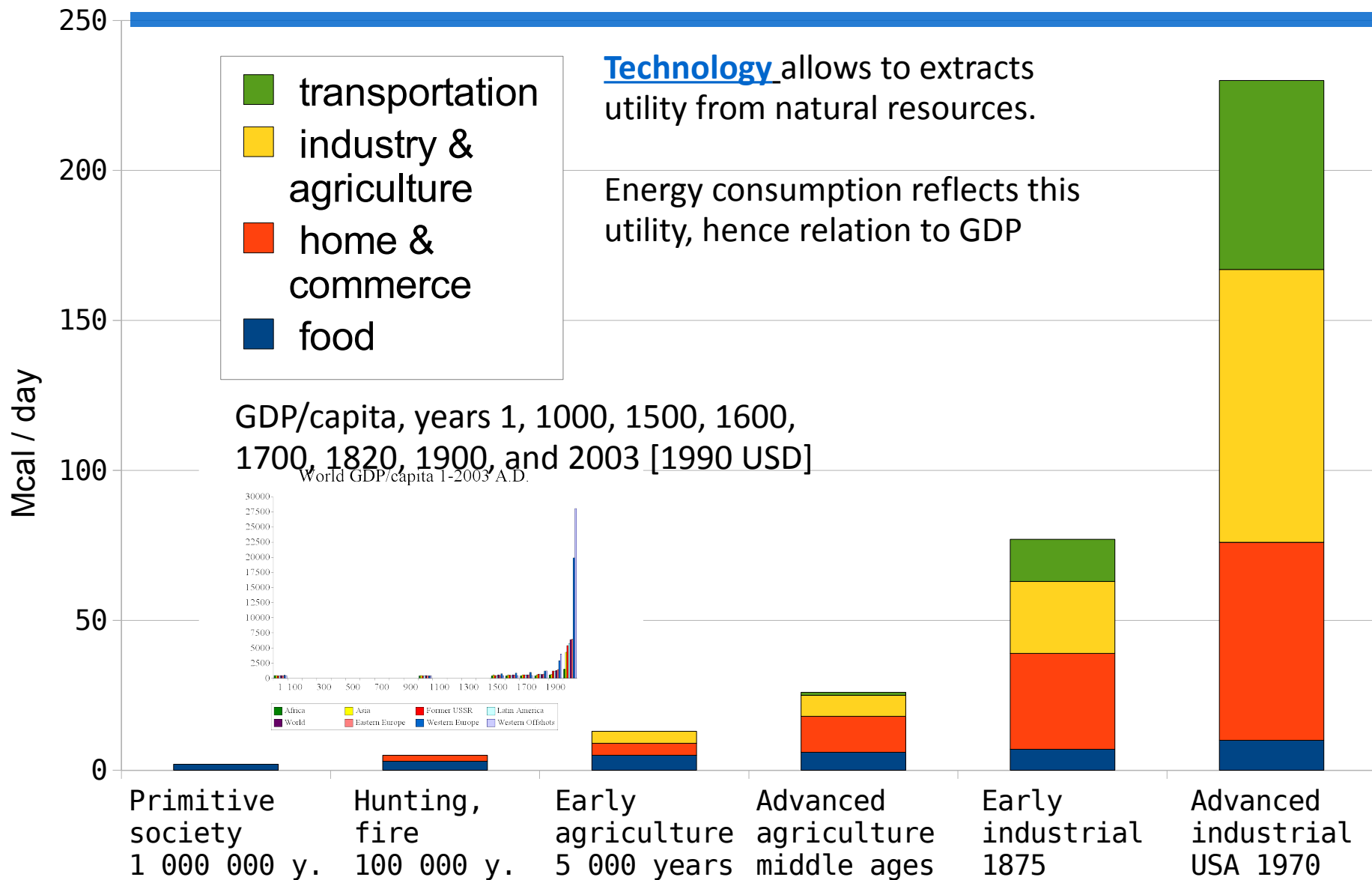
1) History of energy use, societal impacts, prosperity

2) Quantitative comparison of existing energy resources

3) Nuclear energy – can be sustainable?

References: <http://news.bbc.co.uk/2/hi/science/nature/4086809.stm>
<http://www.who.int/mediacentre/factsheets/fs292/en/index.html>
http://www.who.int/quantifying_ehimpacts/national/countryprofile/mapoap/en/index.html

Energy extraction per capita in history



References:

<http://www.wou.edu/las/phisci/GS361/electricity%20generation/HistoricalPerspectives.htm>

http://en.wikipedia.org/wiki/Gross_domestic_product#Standard_of_living_and_GDP

Development of human civilization is closely connected to energy consumption

Energy consumption per capita in several stages of development

Mcal / day	Primitive society 1 000 000 y.	Hunting, fire 100 000 y.	Early agriculture 5 000 years	Advanced agriculture middle ages	Early industrial 1875	Advanced industrial USA 1970
food	2	3	5	6	7	10
home & commerce	0	2	4	12	32	66
industry & agriculture	0	0	4	7	24	91
transportation	0	0	0	1	14	63
total Mcal / day / person	2	5	13	26	77	230
total GJ / year / person	3.1	7.6	19.9	39.7	117.7	351.5
total average kW / person	0.1	0.2	0.6	1.3	3.7	11.1

* <http://www.wou.edu/las/physci/GS361/electricity%20generation/HistoricalPerspectives.htm>

Adapted from: E. Cook, "The Flow of Energy in an Industrial Society" Scientific American, 1971 p. 135.

Total per capita use in technological age is ~100x that of the primitive society

non-SI unit: "Energy slave" (ES) - 8h/day 60 W useful work.

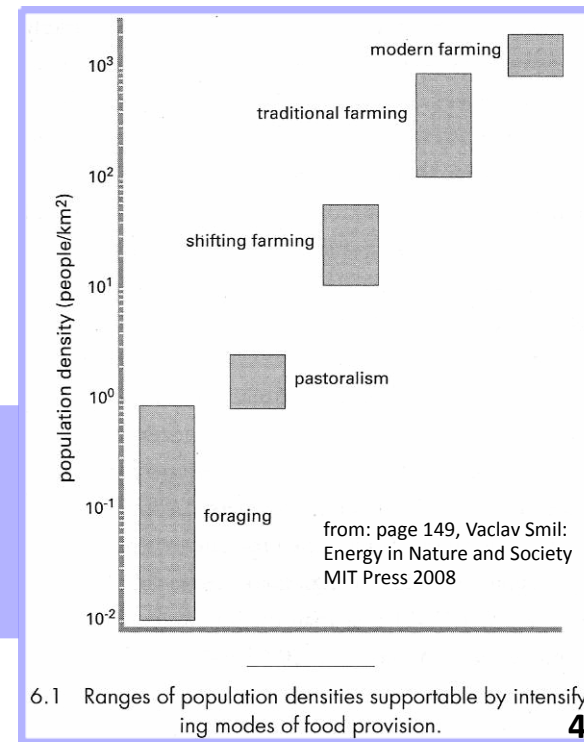
500 energy slaves/capita which heat homes, water, transport people and stuff, drive machines in factories etc.

Can two ES provide a 120W computer? **We live in golden times**

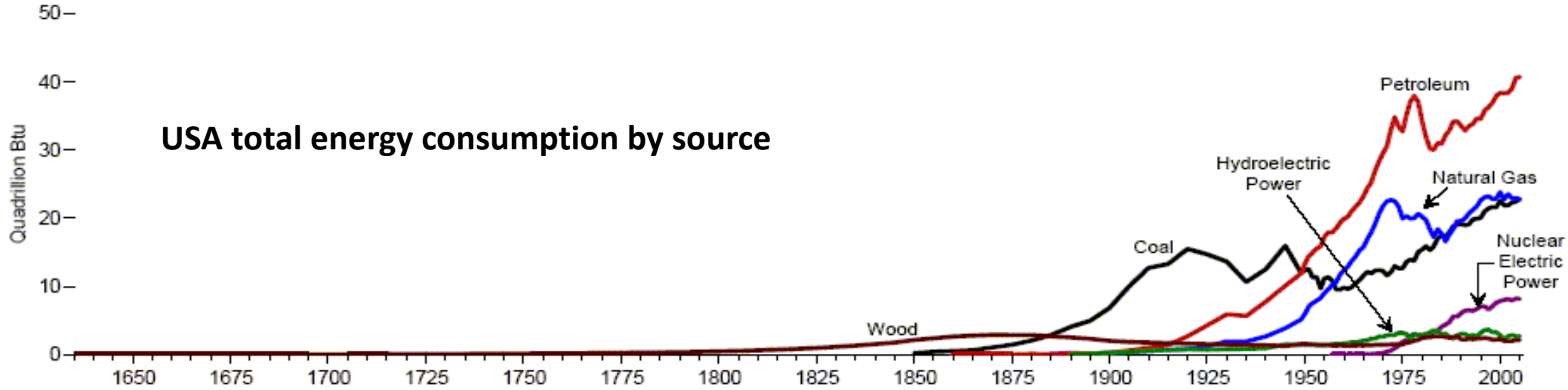
Most of the energy consumption growth occurs and is expected in developing countries (>3G people)

- rising from early industrial-like poverty
- transfer of heavy manufacturing from developed world

"Carrying capacity" for humans depends on civilization stage and resp. technology (now from Haber-Bosch to satellite controlled farming)



USA – historic perspective of energy use

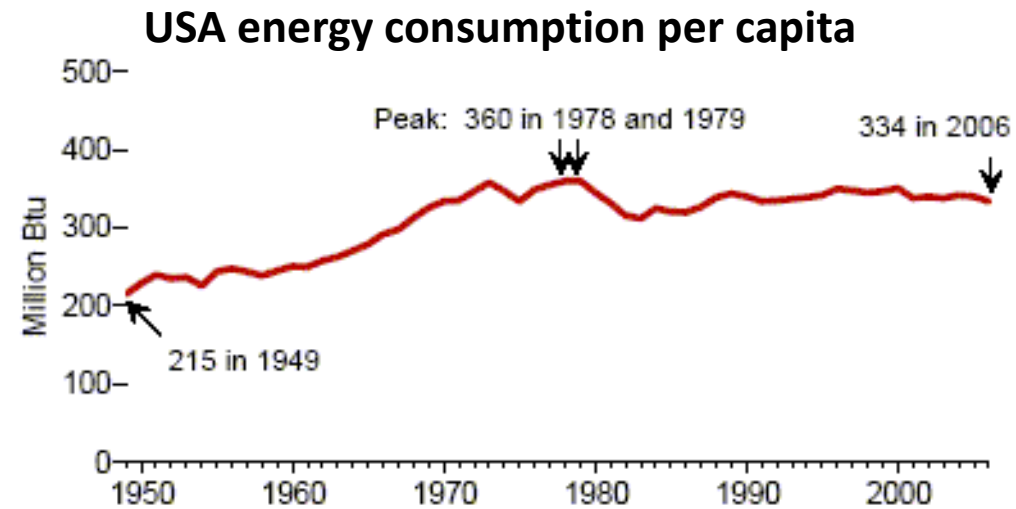


(*) plots from: http://www.eia.doe.gov/emeu/aer/ep/ep_frame.html

Energy consumption per capita is mostly determined by civilization era.

In the technological age, per capita energy consumption growth stops, however we need to change the energy source away from combustion.

Total energy consumption by humans will rise as billions living in 3rd world countries transit from agriculture and industrial civilizations to the technological age.

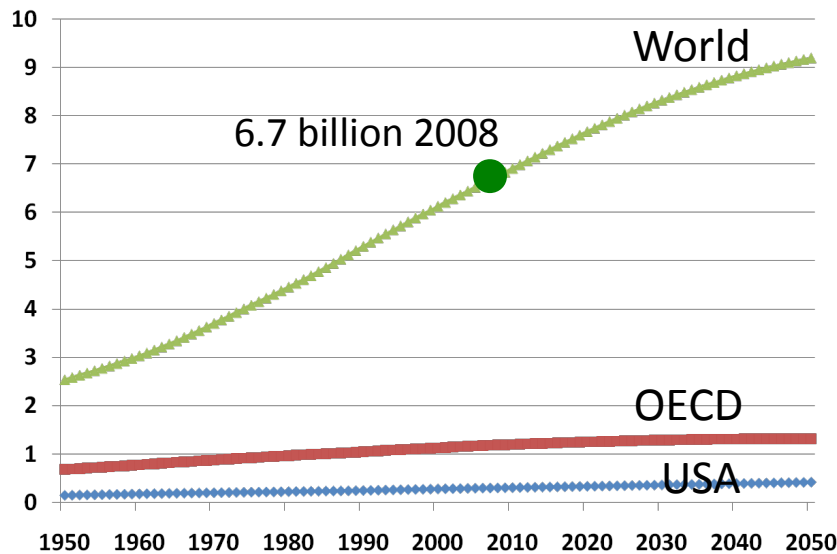


Population

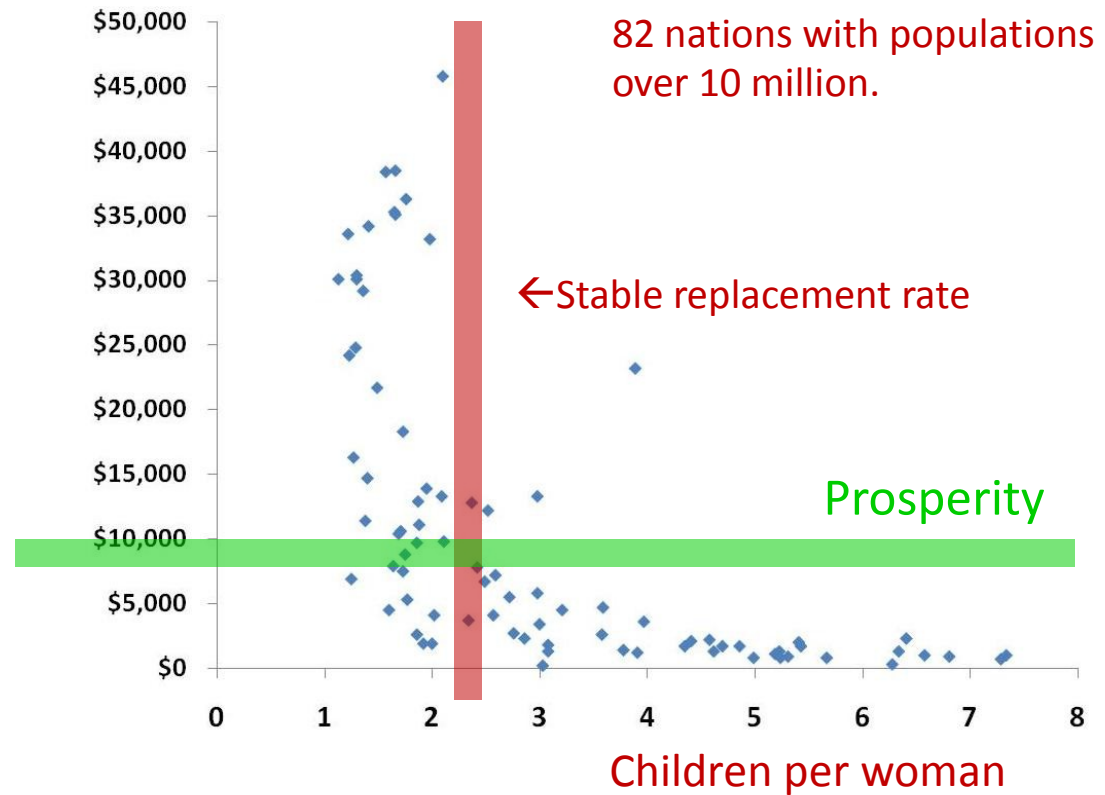
Population is stable in developed countries

Prosperity stabilizes population

Population [billions]



GDP per capita [2007 USD]



<https://www.cia.gov/library/publications/the-world-factbook/docs/rankorderguide.html>

References:

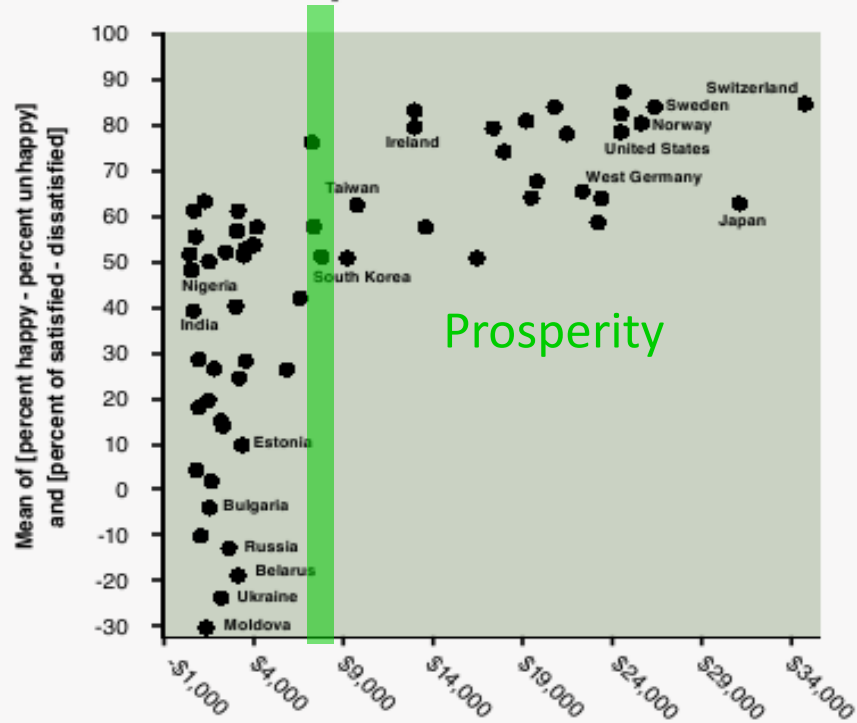
<http://caliban.sourceoecd.org/vl=1260748/cl=17/nw=1/rpsv/factbook/010101.htm>

<http://www.oecd.org/dataoecd/13/38/16587241.pdf>

From: <http://rethinkingnuclearpower.googlepages.com/aimhigh>

Quality of life and energy consumption I

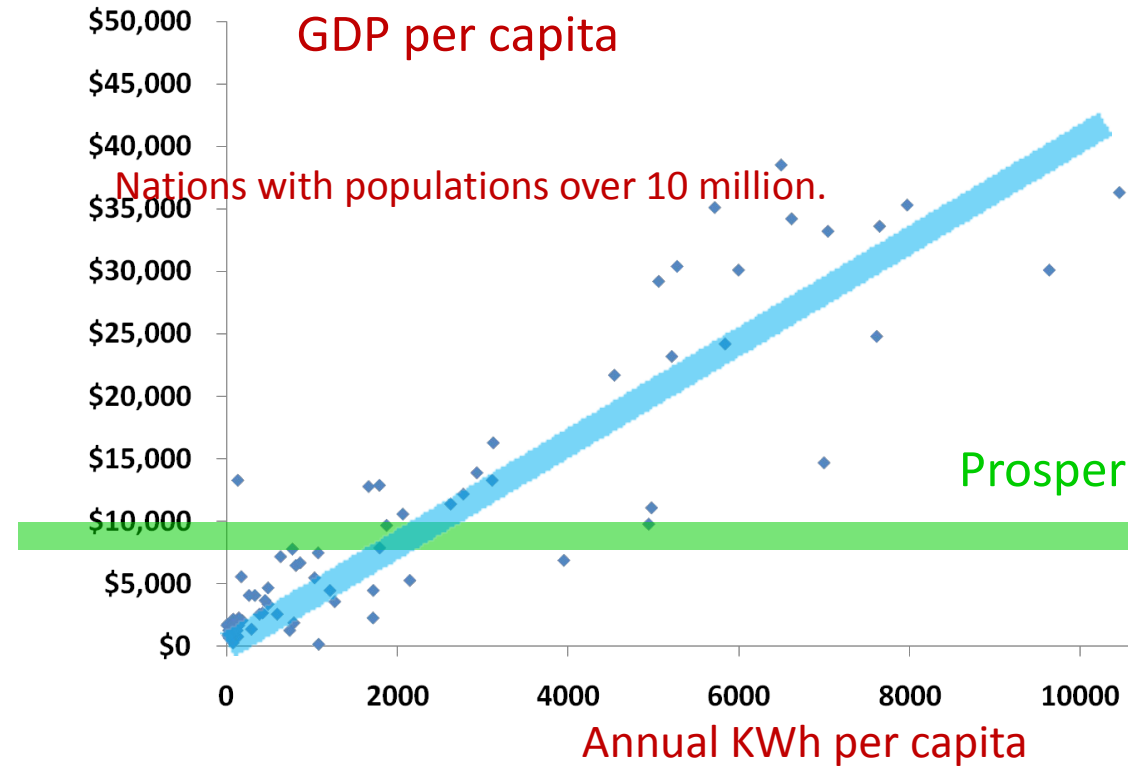
Figure 1. Subjective well-being by level of economic development



Gross national product (GNP) per capita in 1998 U.S. dollars

NOTE: The subjective well-being index reflects the average of the percentage in each country who describe themselves as "very happy" or "happy" minus the percentage who describe themselves as "not very happy" or "unhappy"; and the percentage placing themselves in the 7–10 range, minus the percentage placing themselves in the 1–4 range, on a 10-point scale on which 1 indicates that one is strongly dissatisfied with one's life as a whole, and 10 indicates that one is highly satisfied with one's life as a whole.

SOURCE: R. Inglehart, "Globalization and Postmodern Values," Washington Quarterly 23, no. 1 (1999): 215–228. Subjective well-being data from the 1990 and 1996 World Values Surveys. GNP per capita for 1993 data from World Bank, World Development Report, 1995 (New York: Oxford University Press, 1995).



References:

<http://rethinkingnuclearpower.googlepages.com/aimhigh>

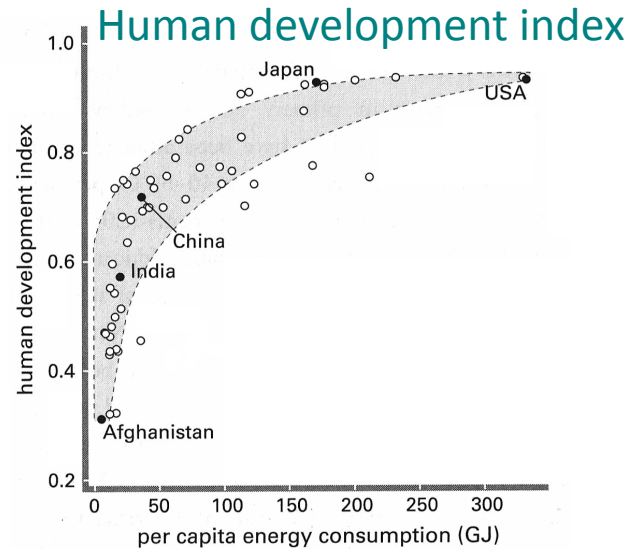
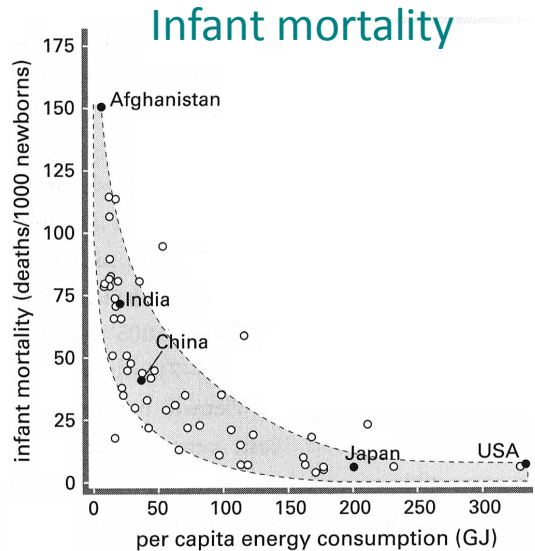
<https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html>

\$7500 (1998) = \$9500 (2007)

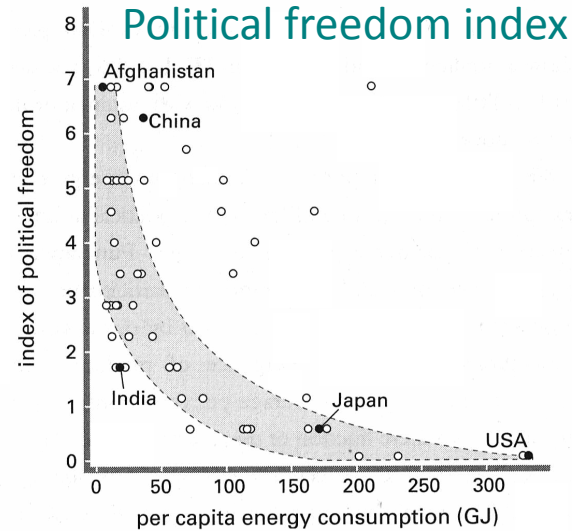
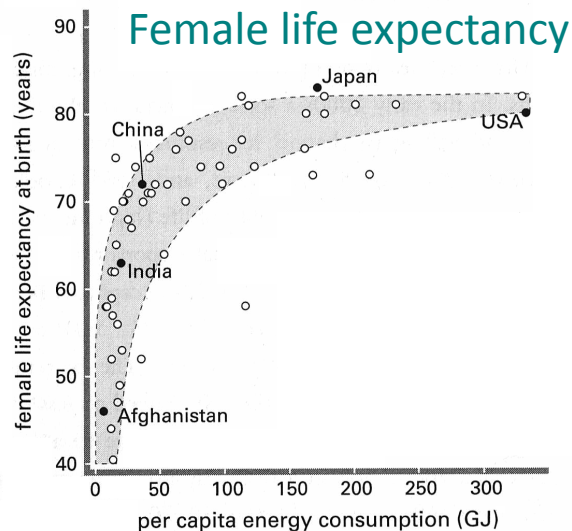
<http://www.westegg.com/inflation/infl.cgi>

Quality of life and energy consumption II

Relationship of several QoL indicators with annual per capita energy consumption



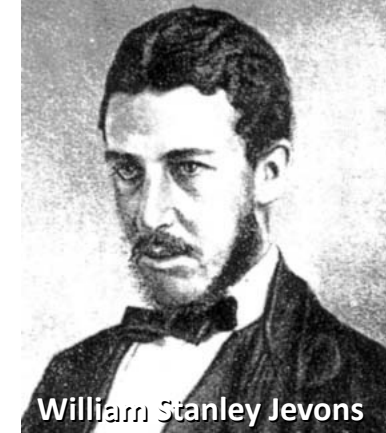
About ½ of US total energy consumption seems to be required for decent standard of living.



High energy use is not a problem
More like a blessing.

from: Vaclav Smil: Energy in Nature and Society, MIT Press 2008, page 347

Conservation and efficiency

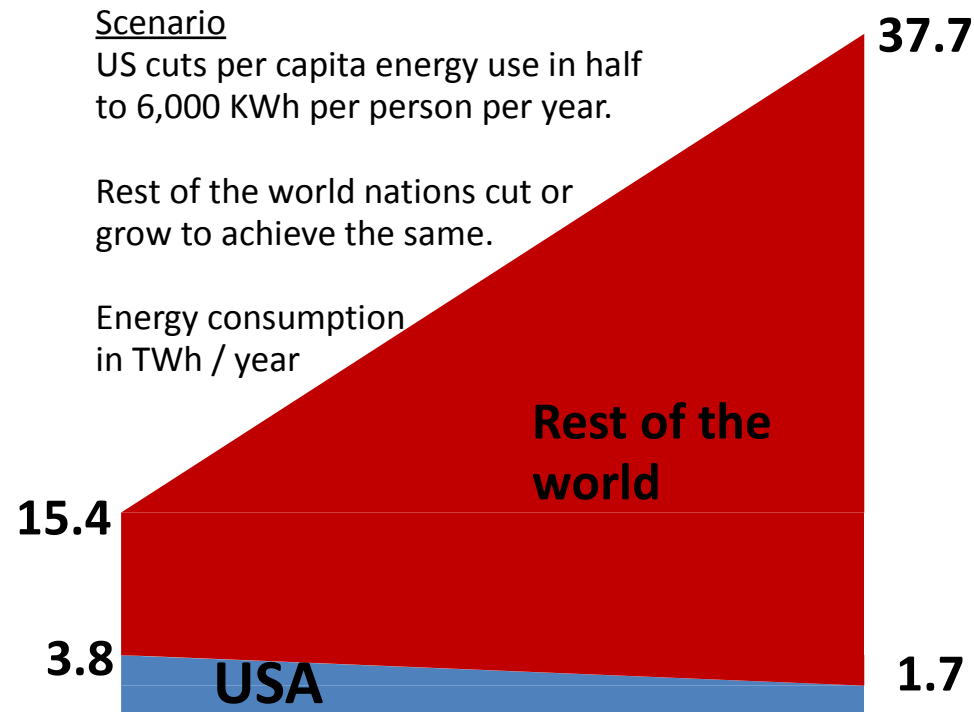


http://en.wikipedia.org/wiki/Jevons_paradox

Energy conservation is economically encouraged (with exceptions such as rental housing)
Lower hanging fruit already collected.
Developing countries need more energy.
Conservation as a solution to energy needs is what starving is to hunger.

Conservation through increasing energy efficiency is inefficient, even futile.

Jevons paradox (1865): increase in efficiency of utilizing a resource increases used quantity of the resource due to a) more work is **substituted** by using of the resource; b) cheaper products increased **disposable income** thus buying more.



Both conservation and increased efficiency are obviously positives, which lead to wealth and prosperity by increasing net income and extracting more utility from less of scarce resource, however:

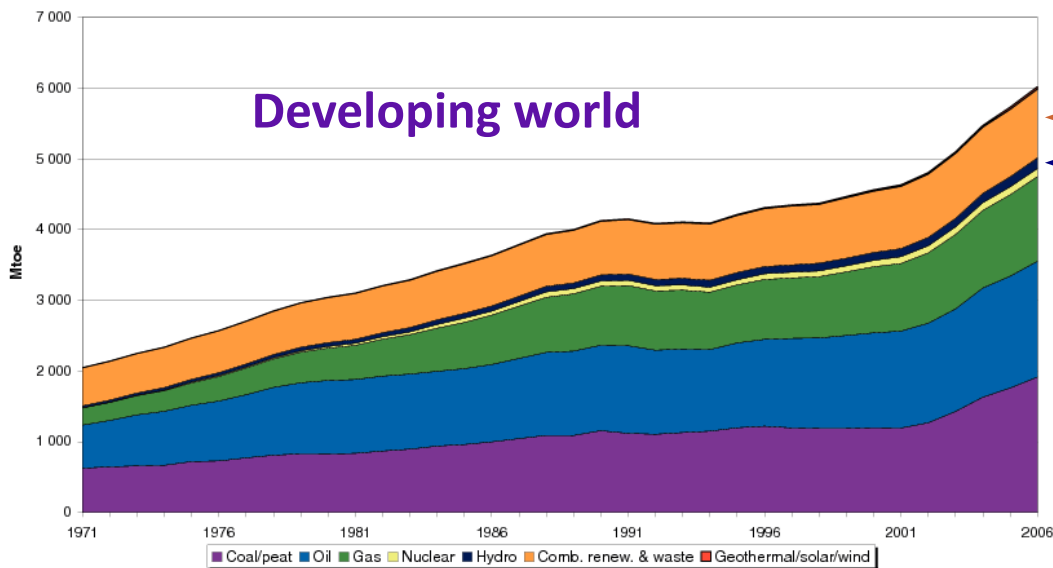
Neither conservation nor efficiency stops global growth of energy use however high energy use as such is not a problem (actually it is beneficial).



Problems with energy production ...

Total primary energy supply*
Non-OECD Total

Developing world



Biomass combustion (wood sticks, trash, animal waste, industrial bio fuels, ...)

Hydro

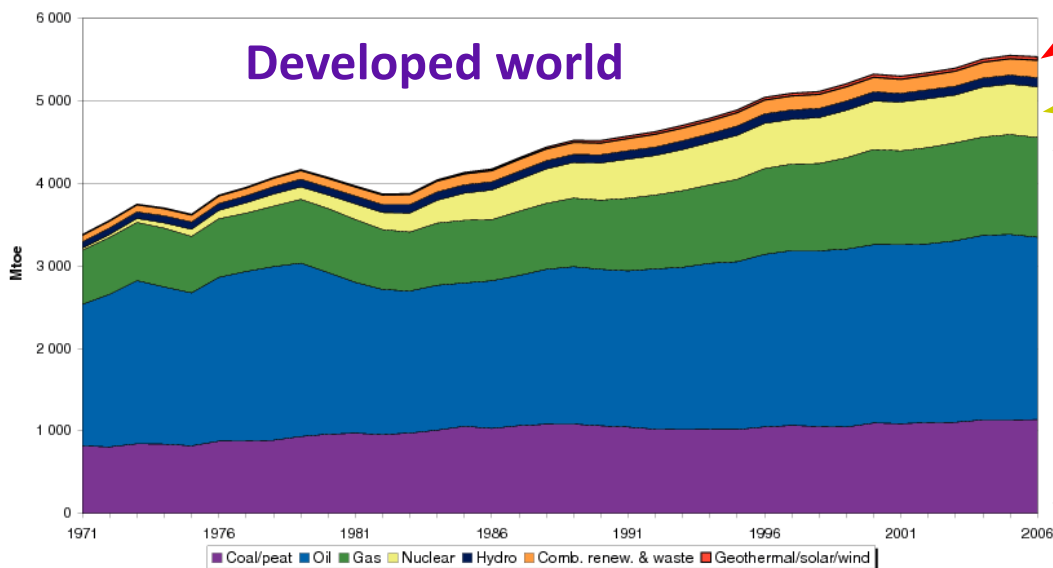
Fossil fuels

Wind+
Solar+
Geothermal+
Tidal+...

... comes by large from combustion of fossils (coal, oil, natural gas)

Total primary energy supply*
OECD30

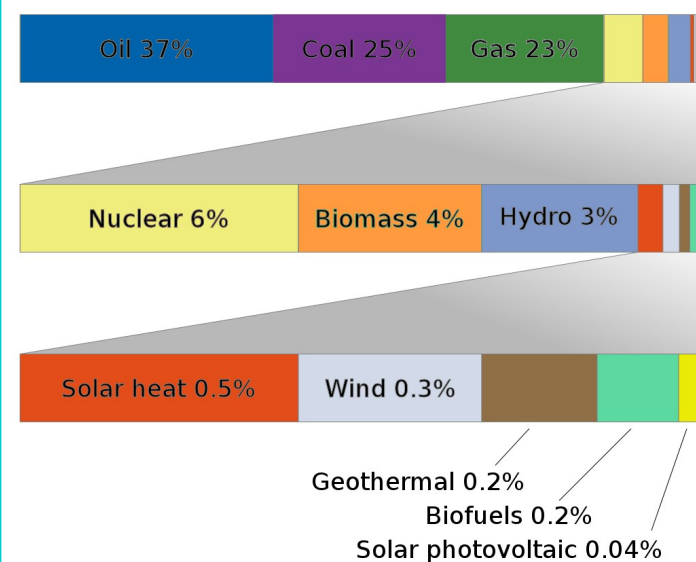
Developed world



Fossil fuels

Nuclear

World energy usage by source



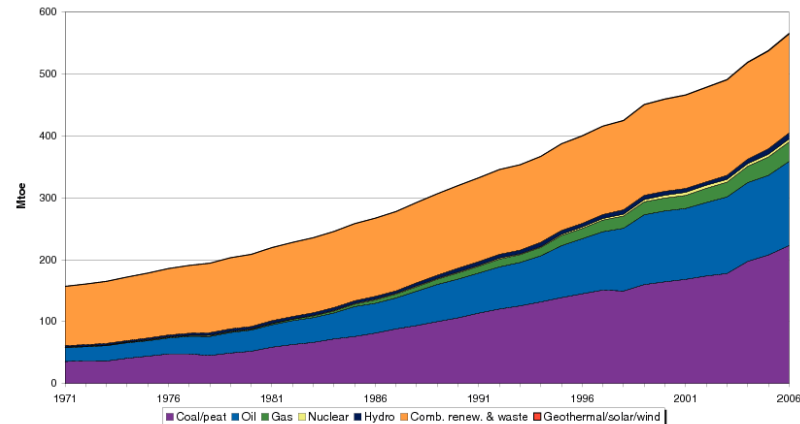
Developing world

Growth of economy and population fueled By increased use of fossil fuels

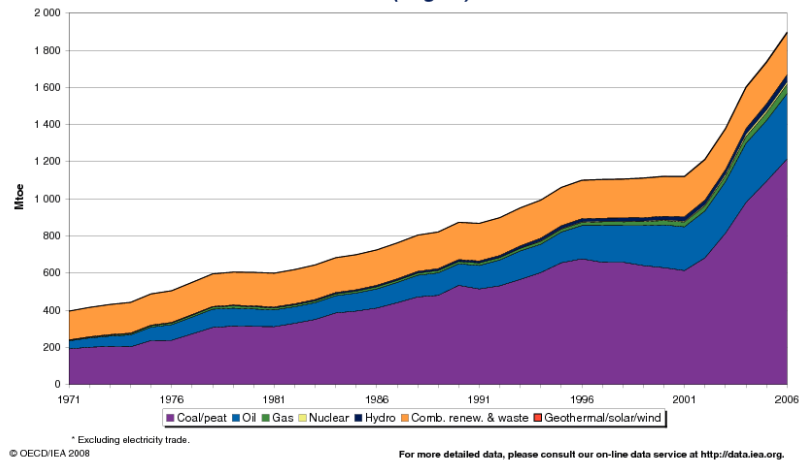
Fossil fuel use growth can be in some cases partially mitigated by use of non-combustion sources.

Efficiency gains from replacing soviet system had realized within 5 to 10 years(!!!)

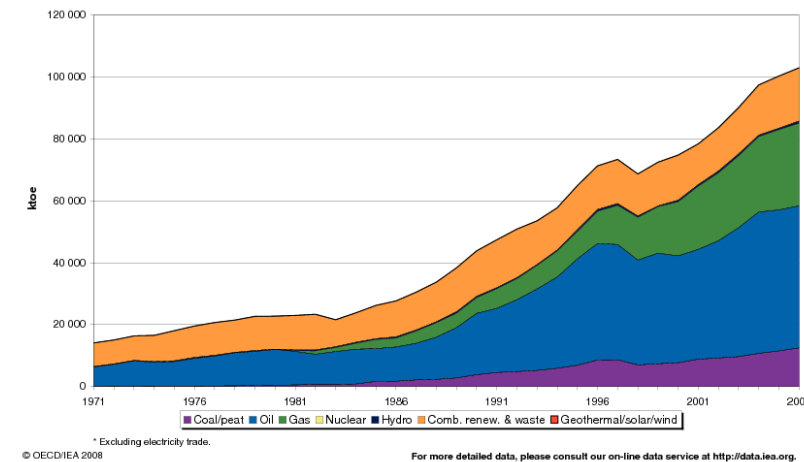
Total primary energy supply*
India



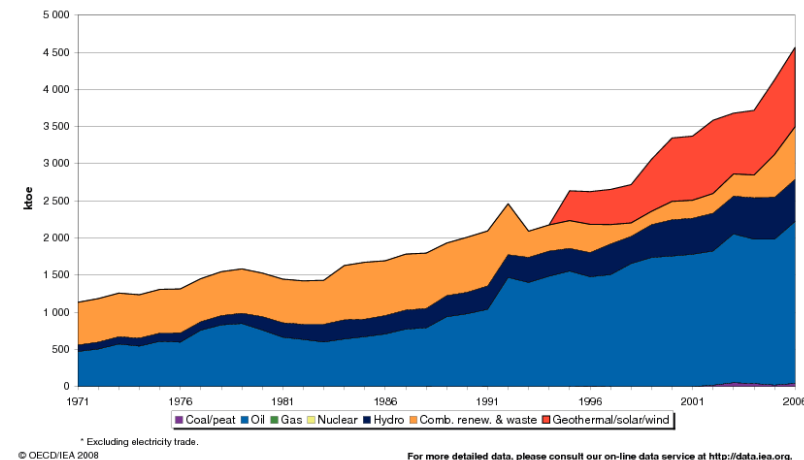
Total primary energy supply*
China (Region)



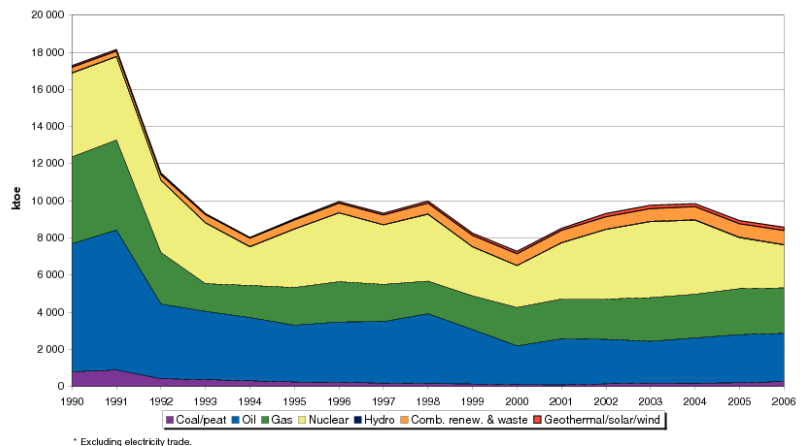
Total primary energy supply*
Thailand



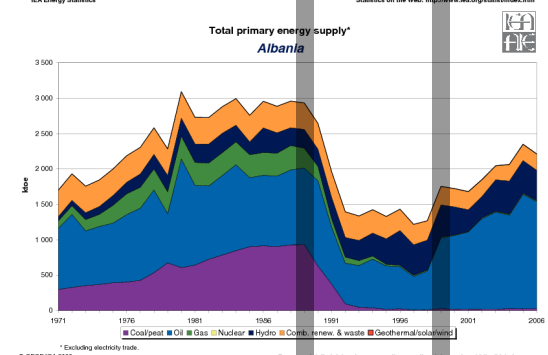
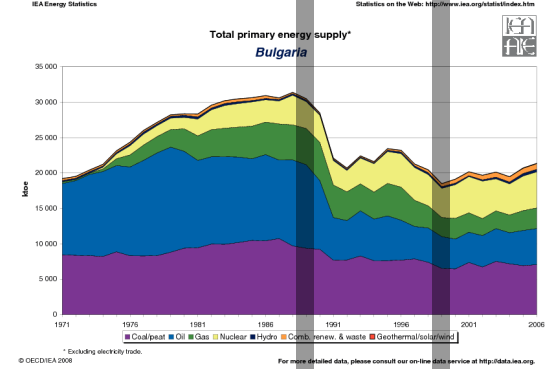
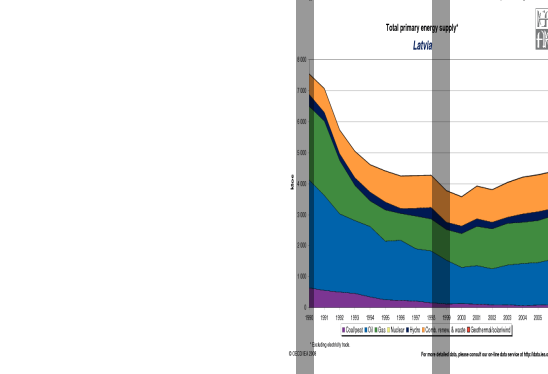
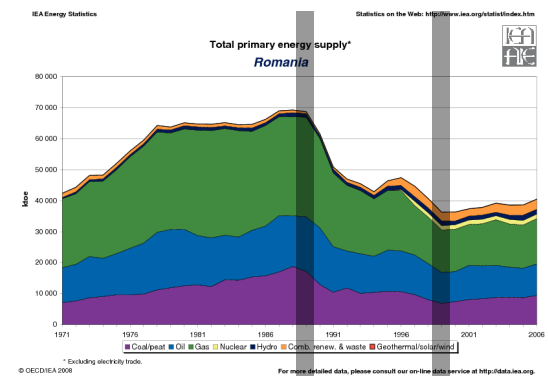
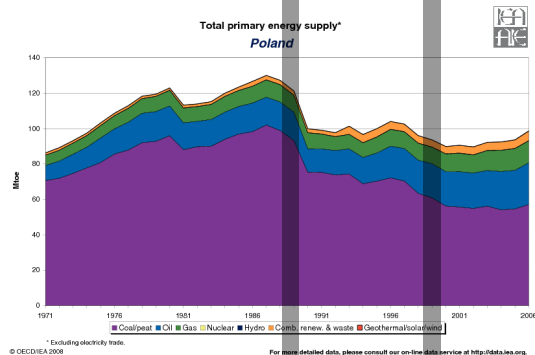
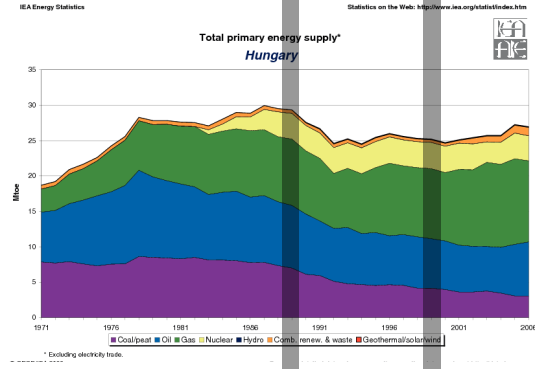
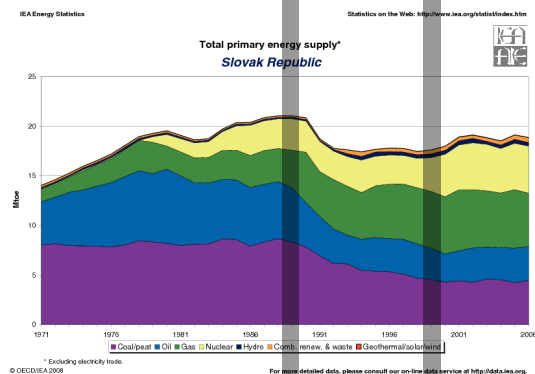
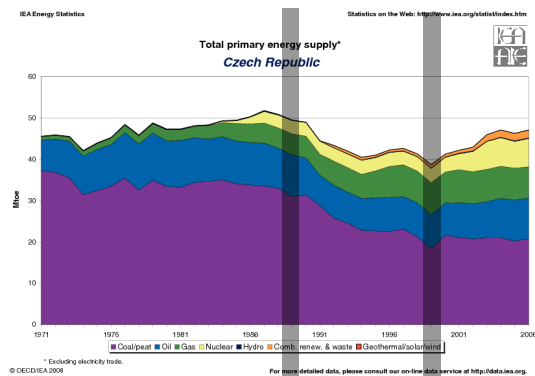
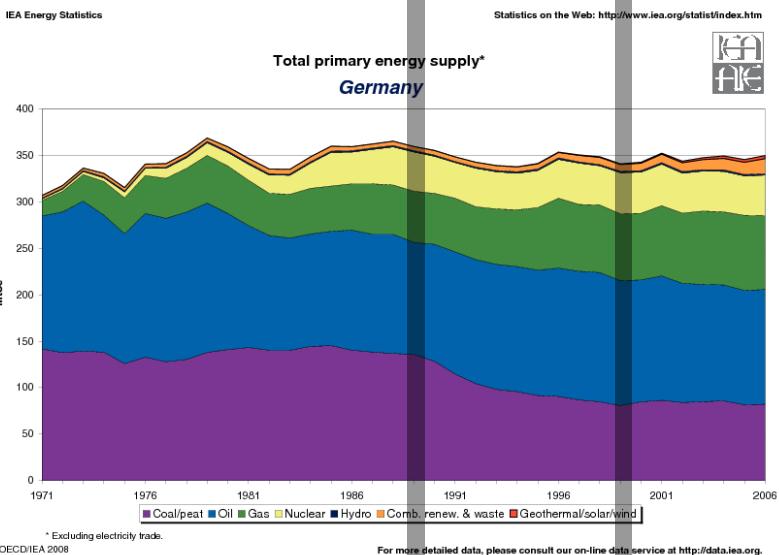
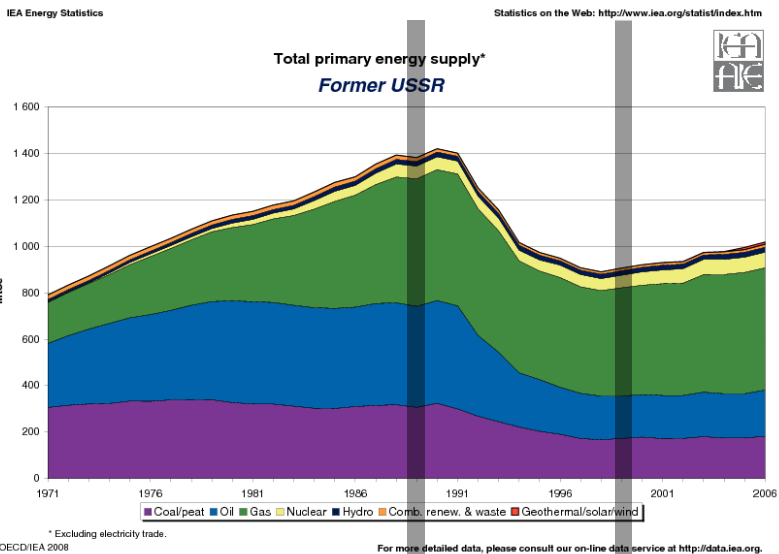
Total primary energy supply*
Costa Rica



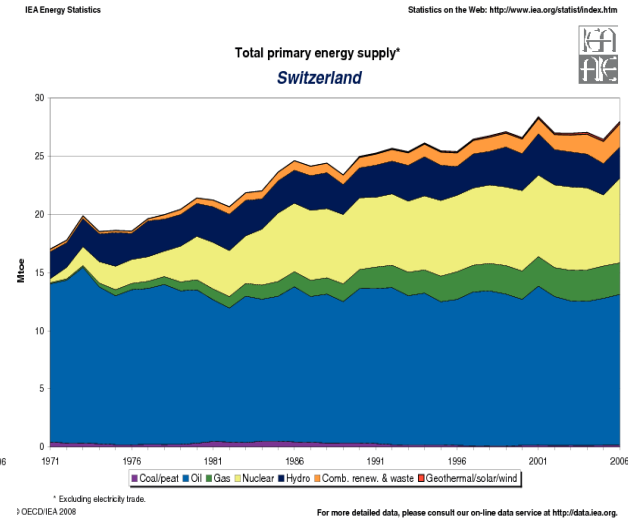
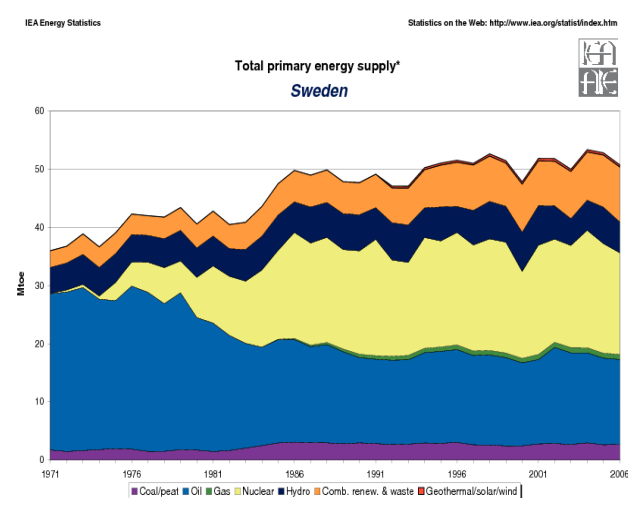
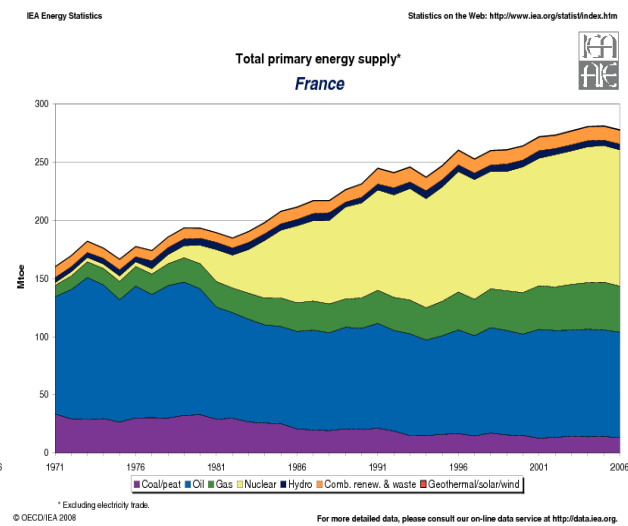
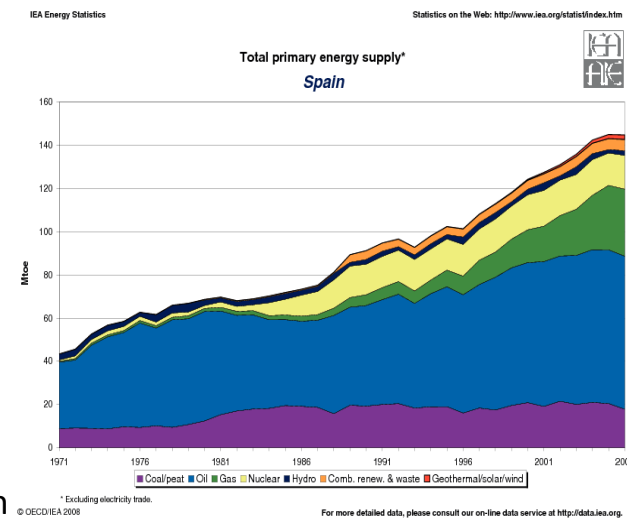
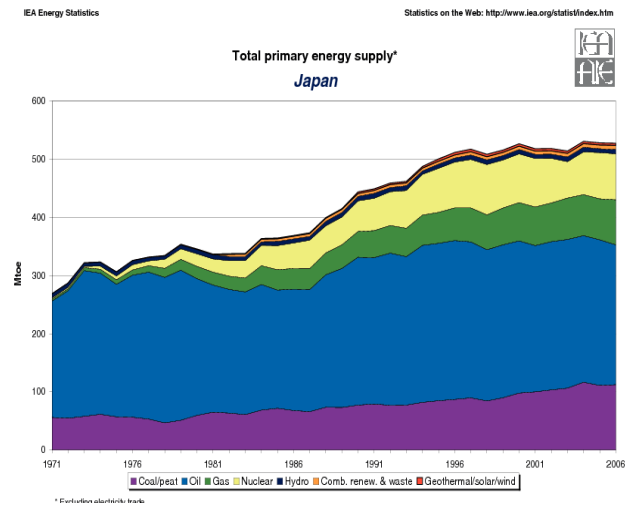
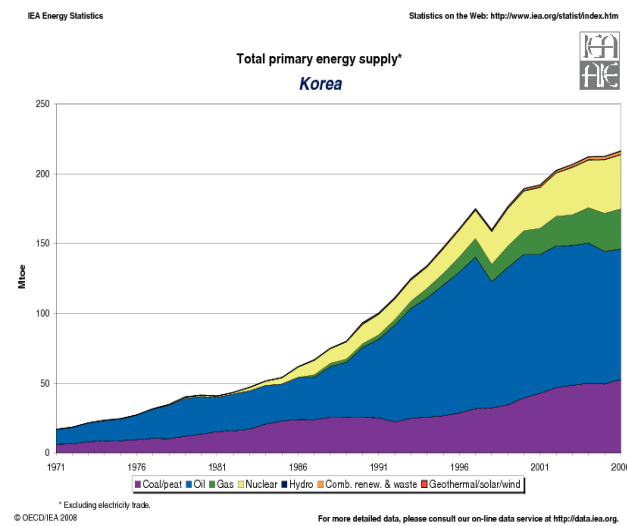
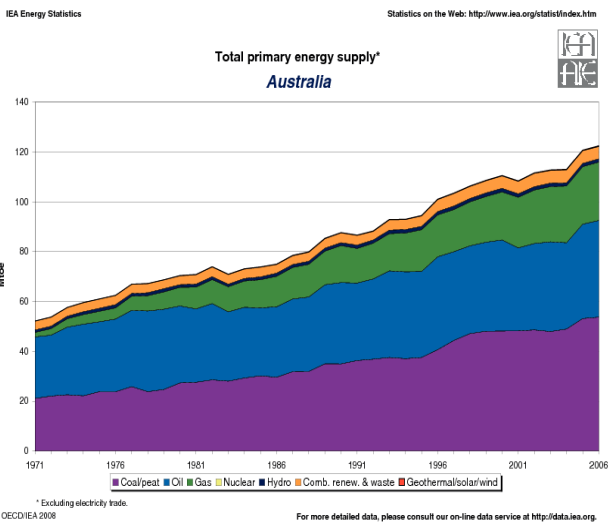
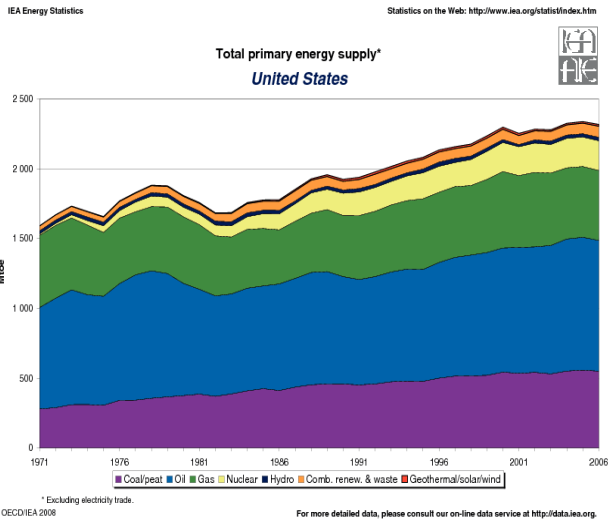
Total primary energy supply*
Lithuania



Transition from Soviet economy 1989-1999



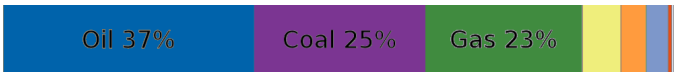
Developed world



Problems with fossil energy production

Price, Availability, Strategic dependence

"We're paying \$700 billion a year for foreign oil" T. Boone Pickens
http://www.usatoday.com/money/industries/energy/2008-07-08-t-boone-pickens-plan-wind-energy_N.htm



Oil: Proved reserves		at end 2007		
		Thousand million barrels	Share of total	R/P ratio
TOTAL WORLD		1237.9	100.0%	41.6
of which: European Union		6.8	0.5%	7.8
OECD		88.3	7.1%	12.6
OPEC		934.7	75.5%	72.7
Former Soviet Union		128.1	10.4%	27.4
Canadian Oil Sands		152.2		
Proved reserves and oil sands		1390.1		
Natural gas: Proved reserves		at end 2007		
		Trillion cubic metres	Share of total	R/P ratio
TOTAL WORLD		177.36	100.0%	60.3
of which: European Union		2.84	1.6%	14.8
OECD		15.77	8.9%	14.4
Former Soviet Union		53.53	30.2%	67.7

Coal: Proved reserves at end 2007			
Million tonnes	Total	Share of Total	R/P ratio
TOTAL WORLD	847488	100.0%	133
of which: European Union	29570	3.5%	50
OECD	356910	42.1%	168
Former Soviet Union	225995	26.7%	463
Other EMEs	264583	31.2%	70

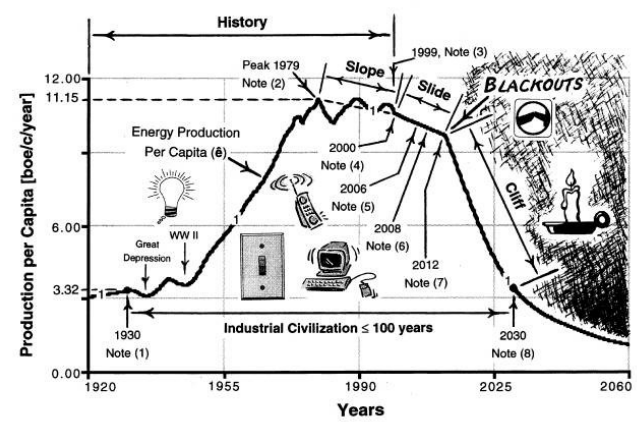
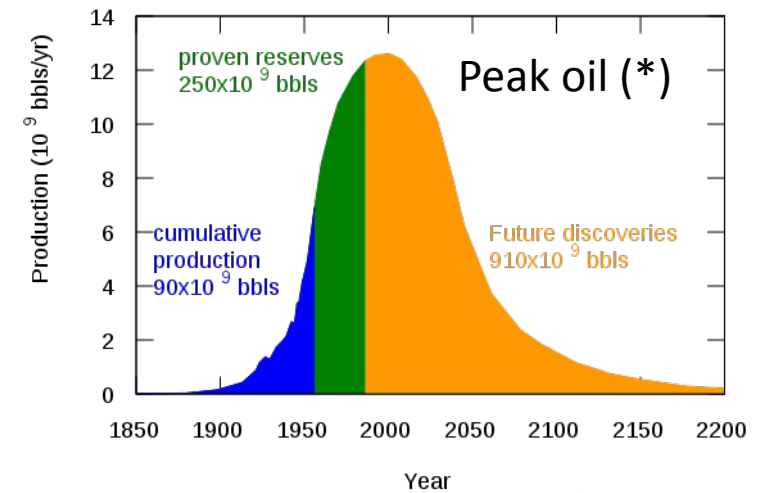
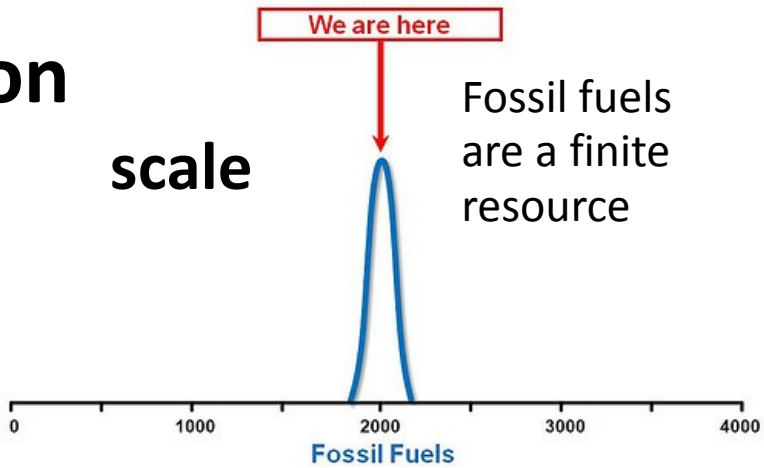
Source of reserves data: Survey of Energy Resources 2007, World Energy Council.
BP: Statistical Review of World Energy 2008
http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/downloads/spreadsheets/statistical_review_full_report_workbook_2008.xls

Ratio of **Reserves to Production** gives years of supply at current rate of consumption

Oil: 42 yR/P
37 % total energy use

Natgas: 60 yR/P
23 % use
"Abundant"???

Coal: 133 y R/P
USDoE Secretary Dr. Chu's "worst nightmare"
Needs to be eliminated by 2030
[J. Hansen et al.]
<http://www.columbia.edu/~jeh1>



Fossils: necessary input for chemical industry (plastics, drugs, fertilizers)

Pollution, Associated risks, Sustainability

(*) for Peak Oil see recent overview Pedro de Almeida, Pedro D. Silva, The peak of oil production--Timings and market recognition, Energy Policy, Volume 37, Issue 4, April 2009, Pages 1267-1276, ISSN 0301-4215, DOI: 10.1016/j.enpol.2008.11.016. (<http://www.sciencedirect.com/science/article/B6V2W-4VC744G-2/2/4090d8bfe324ad1abf44166f357a69f9>)

Electricity – flexible energy

Electricity – the most versatile energy, can be very efficiently transformed to other forms (heating, colling, motion; powering factories, lights, computers ...)

Electricity consumption is rising

Developed countries – electrify transportation

Developing – electricity essential to alleviate poverty

Agriculture: N fixation (Haber-Bosh process) 100M t/year of fertilizers

Currently natgas cheaper (3-5% of world natgas consumption)

http://en.wikipedia.org/wiki/Haber_process

Synthetic fuels: “Los Alamos National Laboratory has developed a low-risk, transformational concept, called **Green Freedom™**, for **large-scale production of carbon-neutral, sulfur-free fuels and organic chemicals from air and water.**” Operating costs \$1.40/gal of synthetic gasoline.

Competitive with gas at pump costs \$4.60/gal (high investment risk), \$3.40 with some improvements

http://www.lanl.gov/news/index.php/fuseaction/home.story/story_id/12554

http://www.lanl.gov/news/newsbulletin/pdf/Green_Freedom_Overview.pdf

Landfills → plasma arc melting Recycles everything but rad-waste

Atomize waste → syngas (CO+H) → chem. feedstock, electricity

→ melted slag – metals separated, partitioned, recycled;

the rest (silicates) → tiles, roadbeds, rock-wool 10x cheaper

1999 Hitachi Metals pilot plant, 2002 car recycling plant

now: 7 plants world wide, 7 under construction

Florida: 910 t waste/day

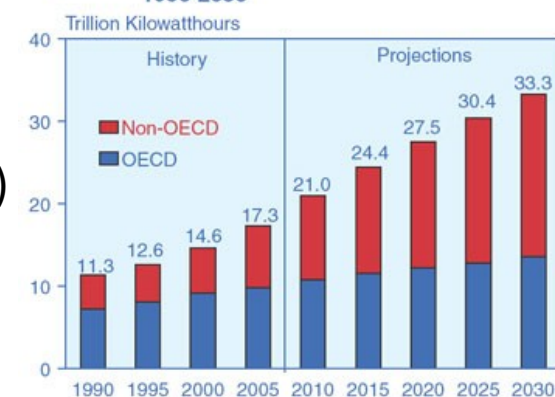
<http://science.howstuffworks.com/plasma-converter.htm>

http://en.wikipedia.org/wiki/Plasma_arc_gasification

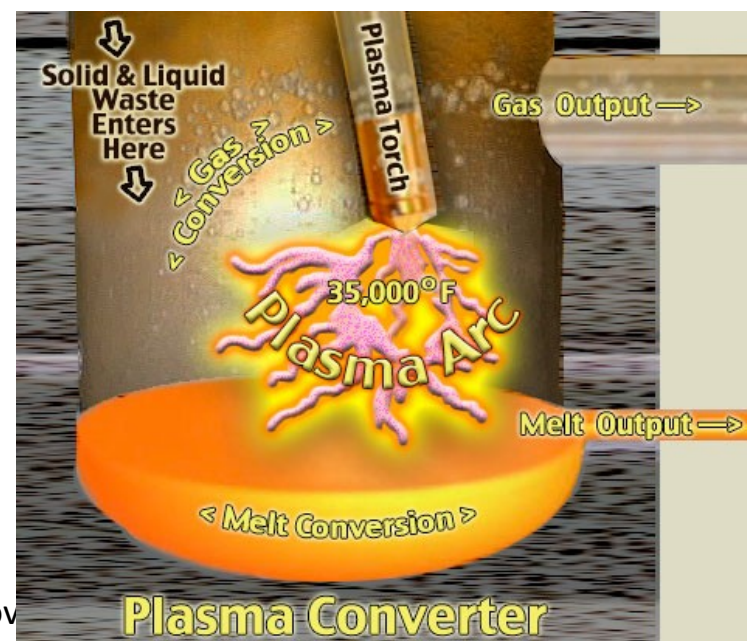
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Figure 53. World Net Electric Power Generation, 1990-2030



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, *System for the Analysis of Global Energy Markets/Global Electricity Module* (2008).

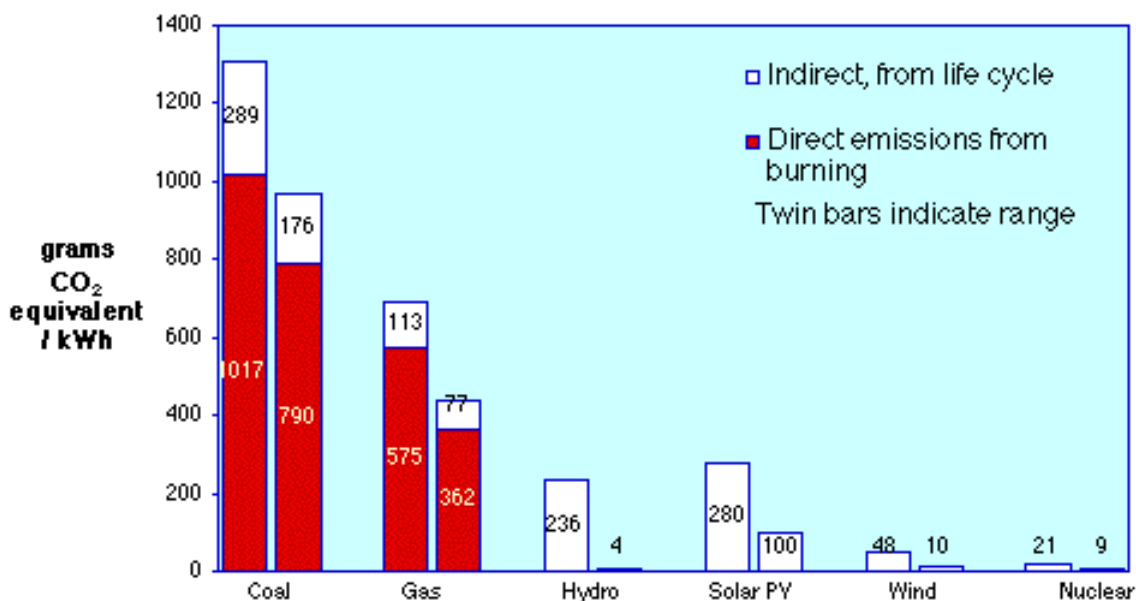


Emissions

Climate Change – emissions of Green-House Gases (GHG) from human activities are the major contributor
40% of US CO₂ emission – electricity generation, coal contributes >80%

Concerning **climate change**, see this article by J. Hansen from NASA GISS:
http://www.columbia.edu/~jeh1/2008/AGUBjerknes_20081217.pdf

Greenhouse Gas Emissions from Electricity Production



Source: IAEA 2000

Life-Cycle analysis of emissions shows:

- **Coal is particularly bad**
- Other fossil fuels are not much better (order: coal, oil, gas)
- Order of magnitude improvements possible only with non-combustion sources

Other combustion pollutants
SO₂, NO_x – acid rain, smog
particulate matter (PM)

arsenic, mercury, cadmium,
uranium, thorium, ... →

toxic fossil waste **“exempted from federal hazardous waste regulations”** [EPA]

<http://www.epa.gov/osw/nonhaz/industrial/special/fossil/index.htm>
<http://www.commondreams.org/headline/2009/01/07-2>

PM emissions (soot) from coal combustion alone are responsible for 24 000 annual deaths in the US.
<http://www.catf.us/publications/view/24>

What is in coal?

	Ppm
Ag	5 – 10
Au	0,2 – 0,5
As	8000
B	8600
Be	2800
Bi	200
Cd	80
Co	2000
Cr	1200
Cs	4
Cu	4000
Ga	6000
Ge	90000
Hg	50
I	950
In	2
La	31
Li	960
Mo	2000
Mn	22000
Nb	2
Ni	16000
Pb	1000
Pt	0,7
Rb	33
Sb	3000
Sc	400
Sn	6000
Ta	0,1
Ti	20000
Tl	25
U	600
V	11000
Y	800
Zn	10000

“The energy content of nuclear fuel released in coal combustion is more than that of the coal consumed!”

<http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html>

More on coal:

<http://pubs.usgs.gov/fs/1997/fs163-97/FS-163-97.html>

<http://energy.er.usgs.gov/products/databases/CoalQual/intro.htm>

<http://www.savethecleanairact.org/factsheet.html>

External costs can be measured: comprehensive study of polluting emissions and their impacts.
See <http://www.externe.info> for details.

External costs for electricity production in the EU (in EUR-cent per kWh)

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AUT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5*			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

* : biomass co-fired with lignites
 ** : sub-total of quantifiable externalities
 (such as global warming, public health, occupational health, material damage)

Solutions - issue dependent
 CFC ban
 SO₂, NO_x – mandatory
 pollution control
 CO₂ – carbon tax

Nuclear is the only
 energy resource which
 pays for externalities
 → spent fuel fund
 → D&D fund

Average **8.6** **4.6** **6.6** **2.0** **1.8** **0.5** **0.6** **0.8** **0.2**
 [USD cents]

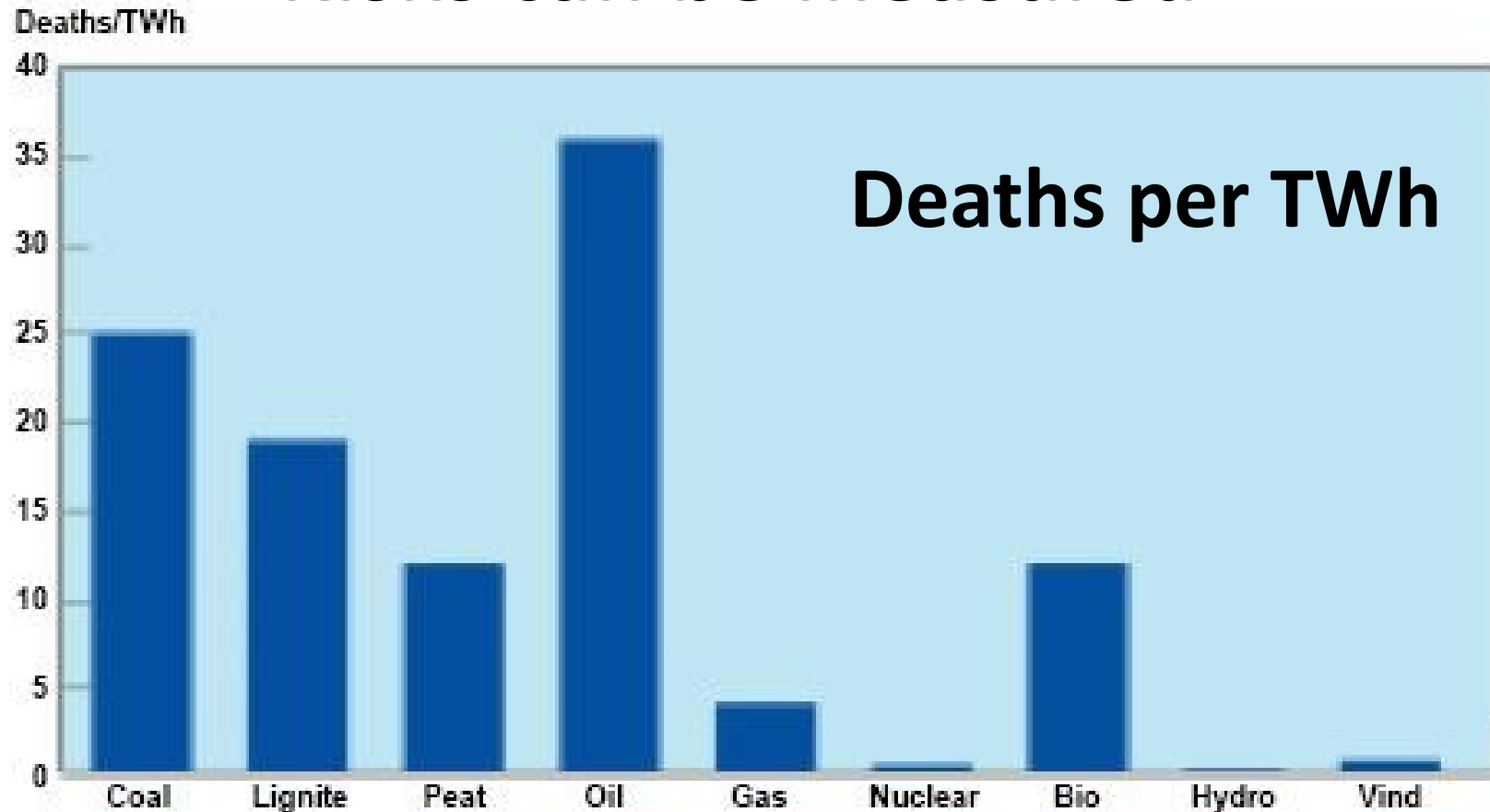
combustion

non-combustion

Including the external price
 would double production cost

Every industrial scale activity is somewhat unsafe

Risks can be measured



References:

<http://www.iaea.org/Publications/Magazines/Bulletin/Bull411/41104991518.pdf>

http://www.eurekalert.org/images/release_graphics/pdf/EH2.pdf

<http://nextbigfuture.com/2008/03/deaths-per-twh-for-all-energy-sources.html>

“In the mid-1990s the mortality rate was actually 0.4 per TWh. The worldwide mortality rate dropped more than half to 0.15 deaths per TWh by the end of 2000.”

<http://www.wind-works.org/articles/BreathLife.html>

<http://www.caithnesswindfarms.co.uk/accidents.pdf>

<http://nuclearpoweryesplease.org/pub/Economic%20Analysis%20of%20Various%20Options%20of%20Electricity%20Generation.pdf>

<http://www3.interscience.wiley.com/journal/119120107/abstract>

<http://depletedcranium.com/?p=1738>

Non-combustion sources
of energy are much safer!

Power Generation Resource Inputs

concrete+steel are > 95% construction costs

- ◆ **Nuclear:** 1970's vintage PWR, 90% capacity factor, 60 year life [1]
 - 40 t steel / MW(average)
 - 190 m3 concrete / MW(average)

- ◆ **Wind:** 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
 - 460 t steel / MW (average)
 - 870 m3 concrete / MW(average)

- ◆ **Coal:** 78% capacity factor, 30 year life [2]
 - 98 t steel / MW(average)
 - 160 m3 concrete / MW(average)

- ◆ **Natural Gas Combined Cycle:** 75% capacity factor, 30 year life [3]
 - 3.3 t steel / MW(average)
 - 27 m3 concrete / MW(average)

1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)

2. S. Pacca and A. Horvath, Environ. Sci. Technol., 36, 3194-3200 (2002).

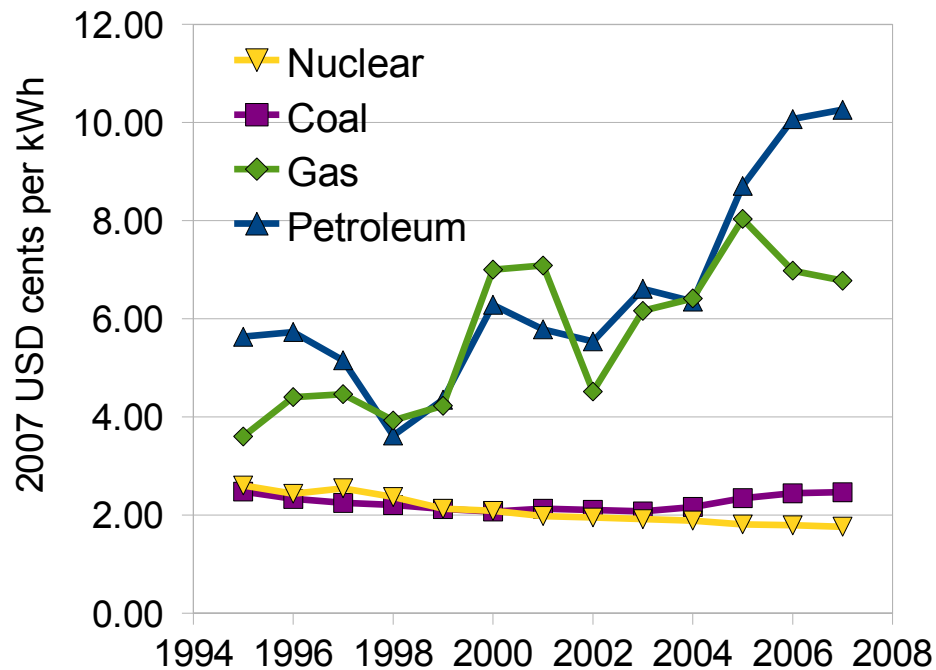
3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. WisconsinReport UWFDm-1181, August, 2002

Cost is essential

Price is crucial, esp. for developing world
Cheap Clean energy – otherwise dirty cheap coal

<http://theenergycollective.com/TheEnergyCollective/37028>
<http://www.youtube.com/watch?v=71kckb8hhOQ>

U.S. Electricity Total Production Costs 1995 - 2007

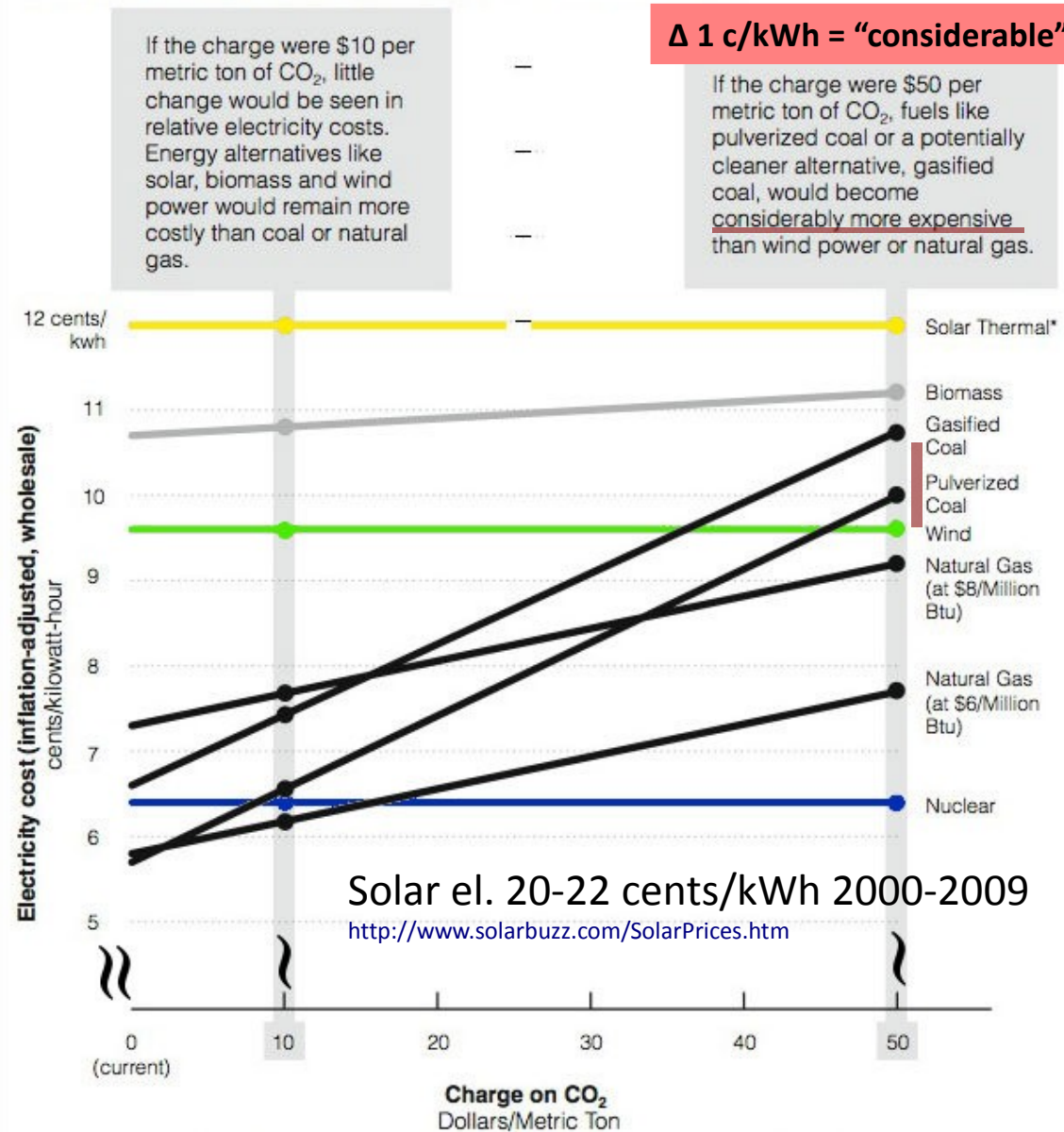


Annual average U.S. electricity production, operations and maintenance (O&M), and fuel costs from 1995 to 2007 for nuclear, coal, gas and oil.

<http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/uselectricityproductioncostsandcompo>

The Cost of Emissions

The graph below shows how a charge on carbon emissions would allow energy sources like solar, wind, or nuclear to compete with coal or natural—as from 2010 to 2015.



*The anticipated cost of solar thermal power is uncertain. Estimates average 19 cents per kilowatt-hour, but can range from 12 cents (best-case scenario, shown) to 26 cents.

<http://www.nytimes.com/2007/11/07/business/businessspecial3/07carbon.html>

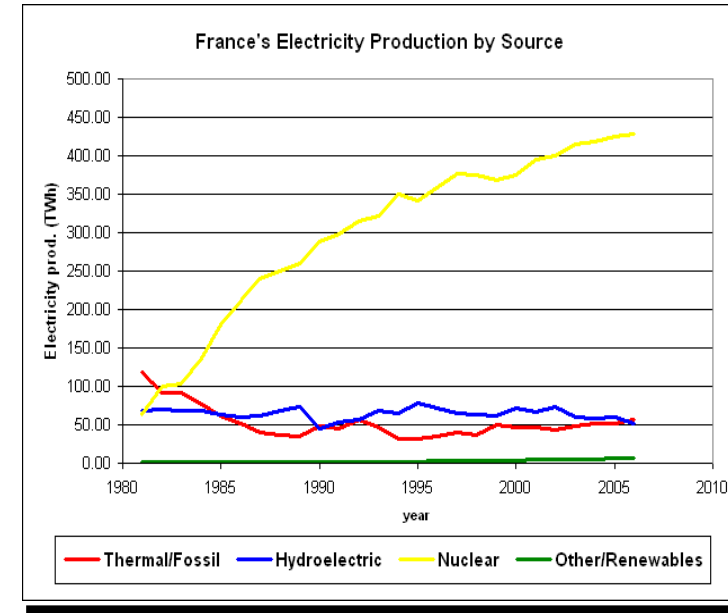
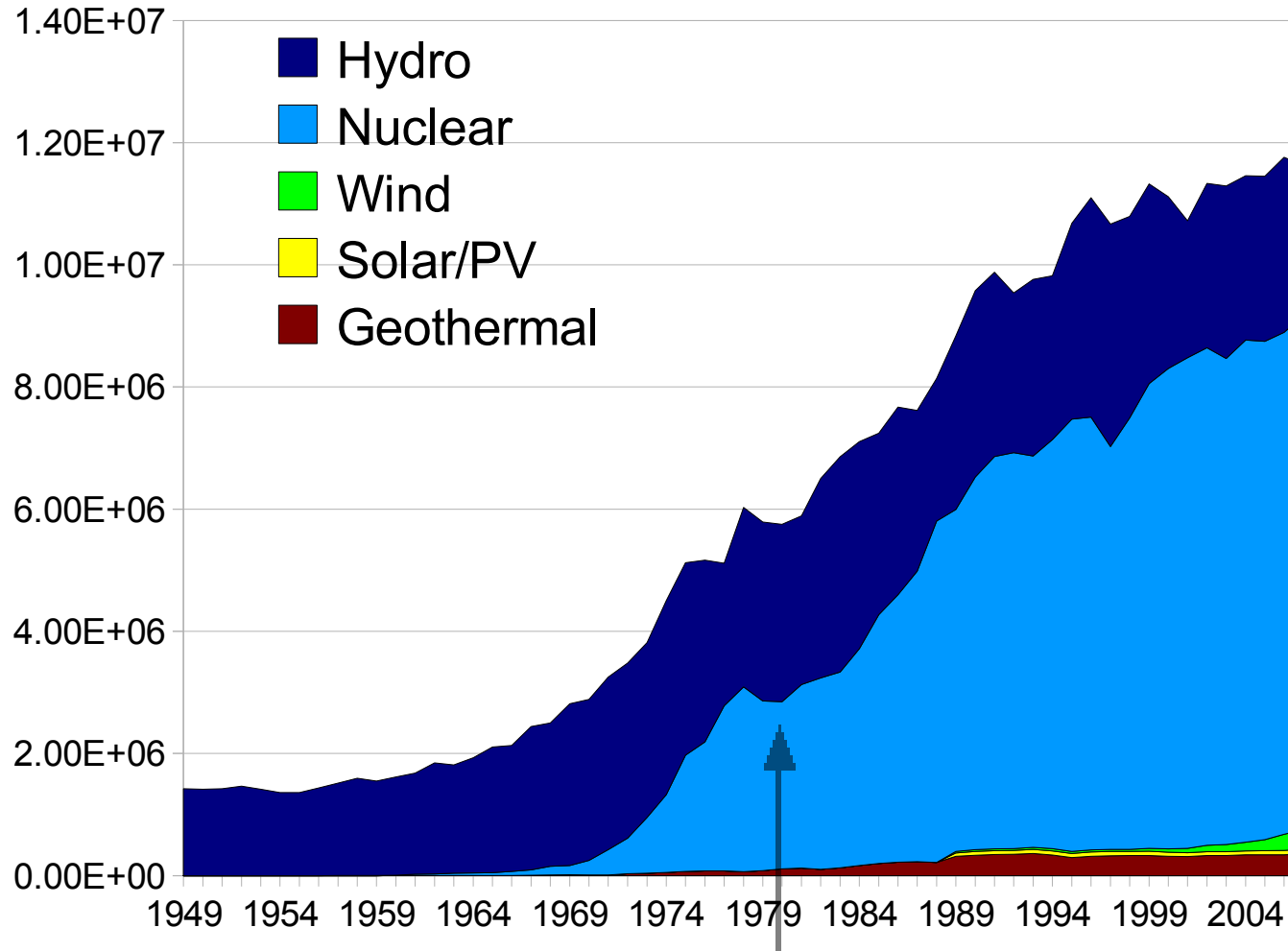
Real Clean energy

Note: France after the 1973 decision went to 80% electricity in about 25 years; closed the last coal mine in 2004

Links:

<http://news.bbc.co.uk/2/hi/europe/3651881.stm>
http://en.wikipedia.org/wiki/Nuclear_power_in_France

U.S. non combustion energy sources (Billion Btu)



NB2: USA EIA 1972 prediction who killed US nuclear power?

<http://www.google.com/search?hl=en&q=smoking%2Bgun+site%3Aato>
http://www.21stcenturysciencetech.com/2006_articles/spring%202006
<http://atomicinsights.blogspot.com/2009/04/anti-nuclear-effectively-means-pr>

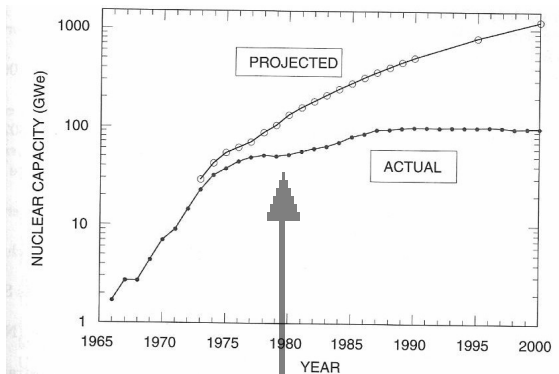


Fig. 2.5. Comparison of U.S. nuclear capacity, projected in 1972 and actual. 1

US Energy Information Agency Table 1.3, The Annual Energy Review, 2007
<http://www.eia.doe.gov/emeu/aer/overview.html>

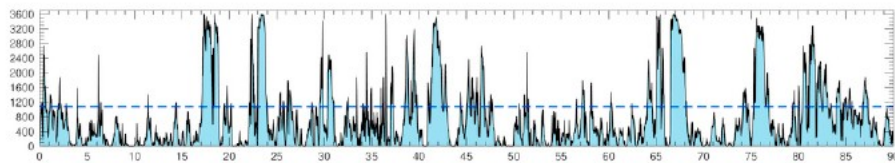
Solar energies

Unrealistic with demonstrated technologies
Invest into R&D (nanotechnology?)

Wind, solar, biomass – the best known (oldest) energy resources
Excellent in particular applications, from calculators to satellites, off grid locations, water pumping, bio-waste use, passive solar heating, ...

Thousands of years spent developing them. Major problems facing large scale deployment still unresolved: **intermittency** → need for energy storage, **low power density** → large demands on raw material (cost) and covered land area (cost, env. impacts)

<http://www.washingtonpost.com/wp-dyn/content/article/2009/04/15/AR2009041503622.html>
<http://phe.rockefeller.edu/docs/HeresiesFinal.pdf>
<http://www.msnbc.msn.com/id/30240000/>

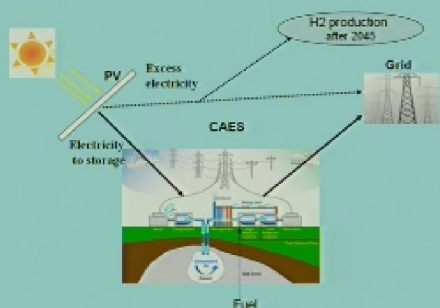


CAES – Compressed Air Energy “Storage”:

“McIntosh CAES plant requires 0.69kWh of electricity and 1.17kWh of gas for each 1.0kWh of electrical output. A non-CAES natural gas plant can be up to 60% efficient therefore uses 1.67kWh of gas per kWh generated. “
http://en.wikipedia.org/wiki/Compressed_air_energy_storage

http://en.wikipedia.org/wiki/Compressed_air_energy_storage

The PV-CAES Conceptual Model



**Real energy storage
R&D needed (also EVs)**

Subsidies to deploy contemporary tech. do not address these issues but lock in contemporary problems

Prices of crystalline-Si PV Modules (average Progress Ratio = 80%)

Module price (log)

Historical Prices

1980

2006 (7.5 GW, \$3.9/W)

Costs have declined due to:
Increase in plant size
Increase in efficiency
Increase in yield
Decreasing Si consumption

Cumulative Production (MWp)

Cumulative prod. (log)

Courtesy R. Margolis, NREL

Mass production issues: toxic pollution from PV panel production (SiCl_4) in China

http://www.treehugger.com/files/2008/03/solar_pollution_china.php

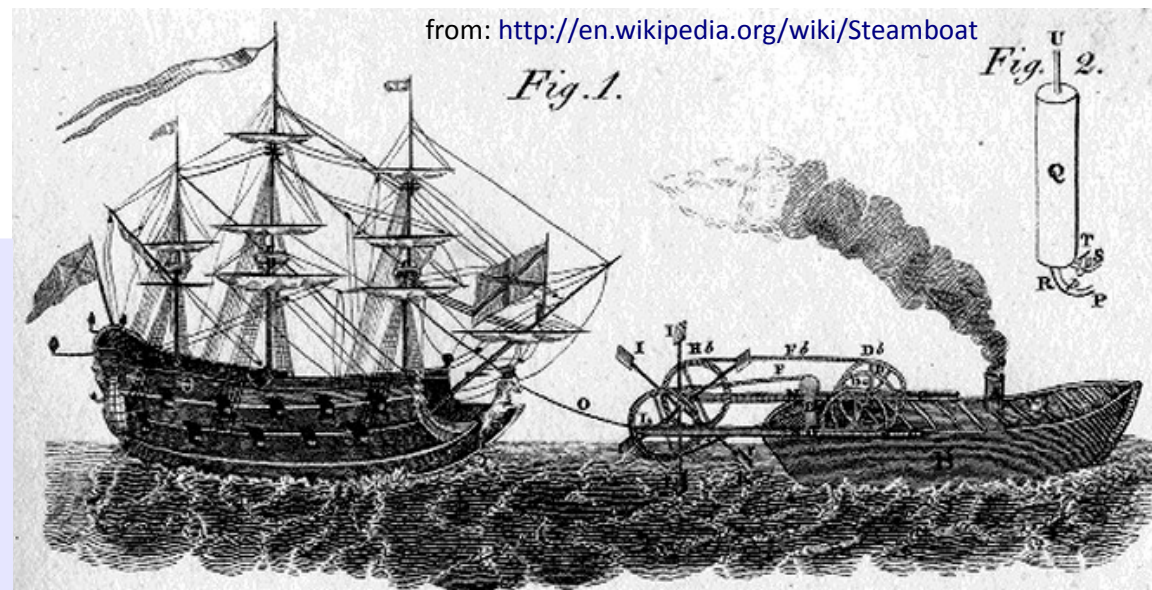
<http://www.washingtonpost.com/wp-dyn/content/article/2008/03/08/AR20080308>

Distribution grid: electricity in = electricity out
Chaotic wind locks in future natgas demand

<http://comste.gov.ph/content.asp?code=292>

<http://www.vtt.fi/inf/pdf/publications/2004/P554.pdf>

Similarity **CAES**: natural gas fired “storage”



“Renewable” energy policy in Europe

Mandated buyouts of “renewable” electricity independently of demand for multiple times the market price

Contra-efficient: Scarce resources → shift of capital from R&D to production of inefficient renewable resource extractors

Driven by rising demand, record high oil and natural gas prices, concerns over energy security and an aversion to nuclear energy, European countries are expected to put into operation about **50 coal-fired plants over the next five years, plants that will be in use for the next five decades.** [NY Times 4/23/2008]

<http://www.nytimes.com/2008/04/23/world/europe/23coal.html>

Cap and trade – Europe spent 50 billion EUR and emission increased
Now **50 new coal power plants** under construction or planned

Germany – renewables are demonstratively not the answer
26 new coal plants under construction or planned
New natural gas pipeline build by Gazprom (51%) and others
Gerhard Schroeder – chairman of the shareholders committee

Austria – replaced Zwentendorf NPP by Dürnrohr coal burner
4 600 MW in natgas burners in construction or planned
imports 10% and rising

France, Sweden, etc demonstrated than nuclear works, and does displace carbon fuels combustion, see slide 13 & 21

References: <http://pathsoflight.us/musing/?p=202>
<http://www.spiegel.de/international/germany/0,1518,472786,00.html>
http://www.businessweek.com/globalbiz/content/mar2007/gb20070321_923592.htm
http://www.businessweek.com/globalbiz/content/feb2009/gb20090210_228781.htm
http://en.wikipedia.org/wiki/Nord_Stream
<http://www.washingtonpost.com/wp-dyn/content/article/2005/12/12/AR2005121201060.html>
[http://ekonomika.ihned.cz/?m=d&article\[id\]=20266960](http://ekonomika.ihned.cz/?m=d&article[id]=20266960)



Dependency on natural gas imports for electricity and heating is also a national security issue

Industrial biofuels = major disaster

Modern industrial agriculture = oil (mech., fertilizers, processing) → food
Burning food?!?

“More fossil energy is used to produce ethanol from corn than the ethanol's calorific value.” T. W. Patzek, UC Berkeley

<http://petroleum.berkeley.edu/papers/patzek/CRPS416-Patzek-Web.pdf>

“Sugarcane-for-ethanol plantation in Brazil could be "sustainable" if the cane ethanol powered a 60%-efficient fuel cell that does not exist.”

<http://petroleum.berkeley.edu/papers/patzek/CRPS-BiomassPaper.pdf>

Environmental wreckage from intensive agriculture <http://www.biofuelwatch.org.uk/>

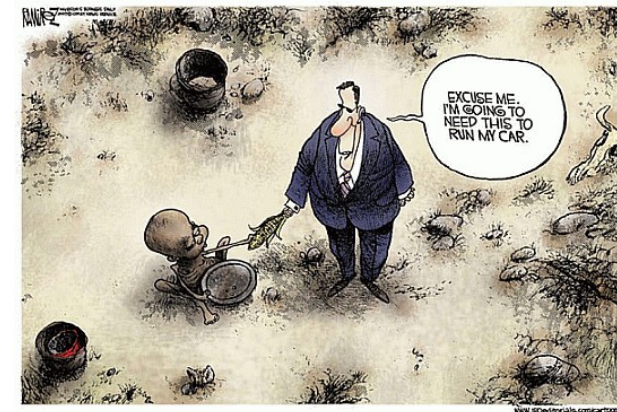
Competition for scarce resources (land, labor, energy) with food crops increases food prices
→ 100 M people pushed to poverty <http://www.nytimes.com/2008/10/08/world/europe/08italy.html?ref=world>

Actually spend more fossil inputs for the same distance traveled, “Biofuels make climate change worse”
<http://www.independent.co.uk/environment/climate-change/biofuels-make-climate-change-worse-scientific-study-concludes-779811.html>

OECD report: “The rush to energy crops threatens to cause food shortages and damage to biodiversity with limited benefits”
<http://media.ft.com/cms/fb8b5078-5fdb-11dc-b0fe-0000779fd2ac.pdf>

UN experts calling to **stop subsidizing biofuels immediately**
<http://www.livescience.com/environment/071027-ap-biofuel-crime.html>

Perhaps oceanic algae? – closed cycle
<http://www.nrel.gov/docs/legosti/fy98/24190.pdf> <http://www.oilgae.com/>
<http://www.popularmechanics.com/science/earth/4213775.html>



Waste biomass works,
but already all used

Jean Ziegler, UN Special Rapporteur for Right for Food, condemns biofuels.



“This is an imminent massacre,” Ziegler warned. He said that while families in the well-off West spent only about 10 percent to 20 percent of their budgets on food, those in the poorest countries

laid out 60 percent to 90 percent. “It’s a question of survival.”

He blamed the crisis on “the indifference of the rulers of the world”, and singled out the US support of bio-fuels for particularly harsh criticism.

“When a bio-fuel policy is launched in the United States, thanks to subsidies of 6 billion of bio-fuels that drains corn from the market, the foundation is laid for a crime against humanity to satisfy one’s own thirst for fuel,” Ziegler charged.

<http://www.dispatch.co.za/article.aspx?id=192811>

(*) Stolen from Robert Hargraves
<http://rethinkingnuclearpower.googlepages.com/aimhigh>

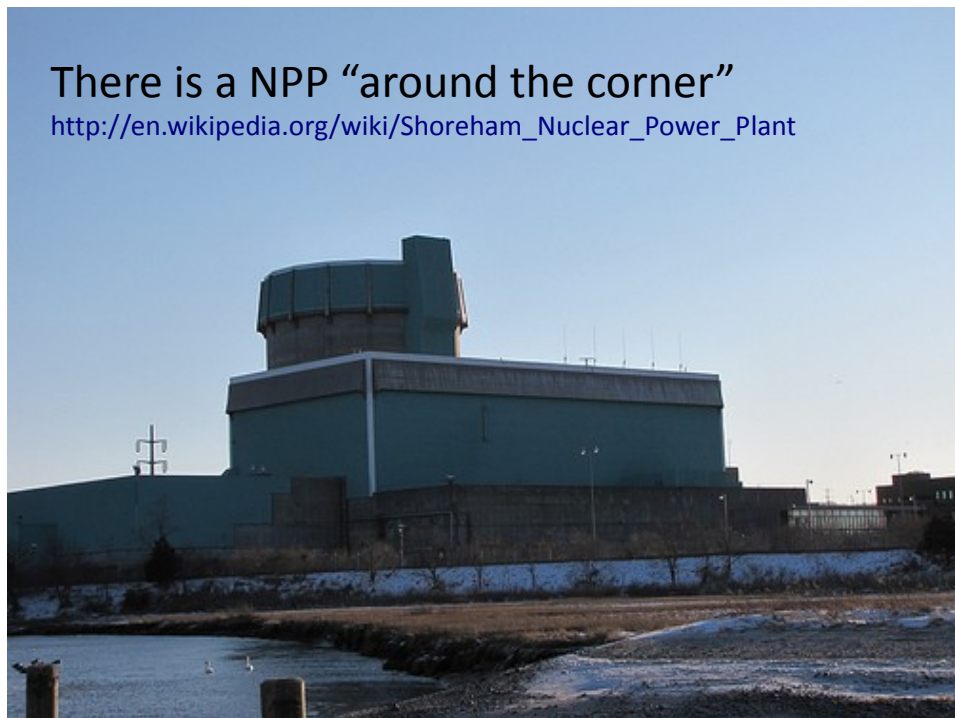
What about Long Island? Ask EPA!

Where does your electricity come from?

<http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html>

There is a NPP “around the corner”

http://en.wikipedia.org/wiki/Shoreham_Nuclear_Power_Plant



Electricity source	[%] 11973
Oil	59.1
Natgas	34.7
Non-hydro renew. (waste inc.)	3.3
Nuclear	0
Coal	0
Hydro	0

If some says “nuclear does not help with oil problem”, beware.

Similar case in Austria:

Start Zwentendorf!

<http://plarmy.org/zwentendorf/en/>

Start Shoreham? E-mail me if interested!

Contemporary nuclear energy

Originates in 1950's navy reactors:
1953 reactor, 1955 Nautilus

Nautilus museum <http://www.ussnautilus.org>
http://en.wikipedia.org/wiki/S1W_reactor

By large PWRs: UO₂ fuel, 5% enrichment,
pressurized vessel, water coolant,
steam generators, steam plant

World: **436** operating, **44** in construction,
110 ordered/planned, **272** proposed

<http://www.world-nuclear.com/info/reactors.html>

USA: **104** operating, **32** new orders in US-NRC pipeline

<http://www.nrc.gov/reactors/new-reactors.html>

Small modular reactors

Toshiba 4S, Westinghouse IRIS, nuScale PWR, Hyperion, NEREUS

<http://www.world-nuclear.org/info/inf33.html>

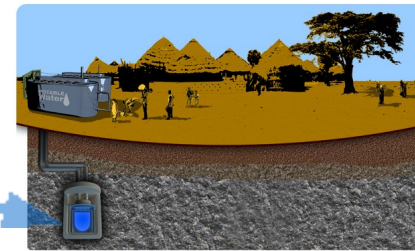
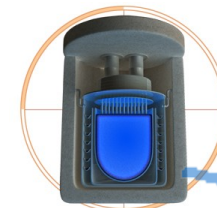
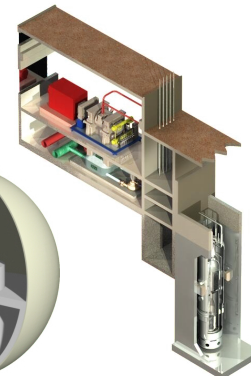
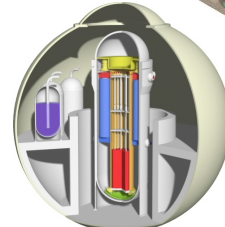
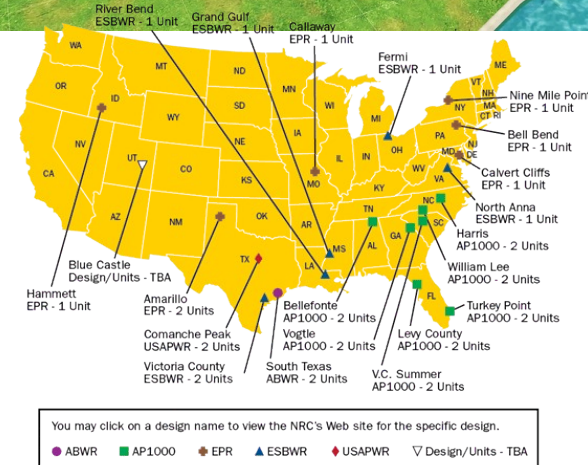
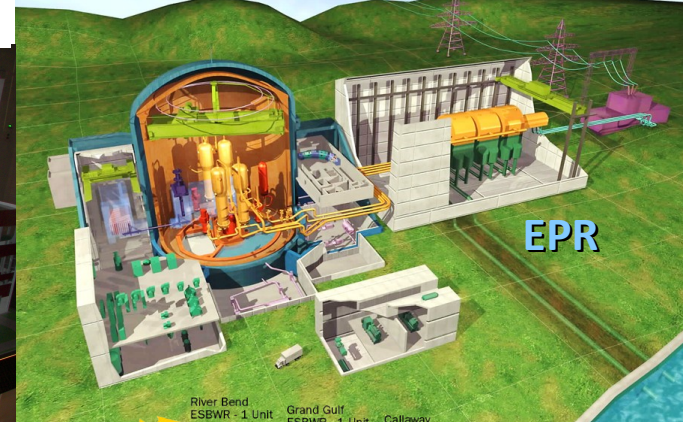
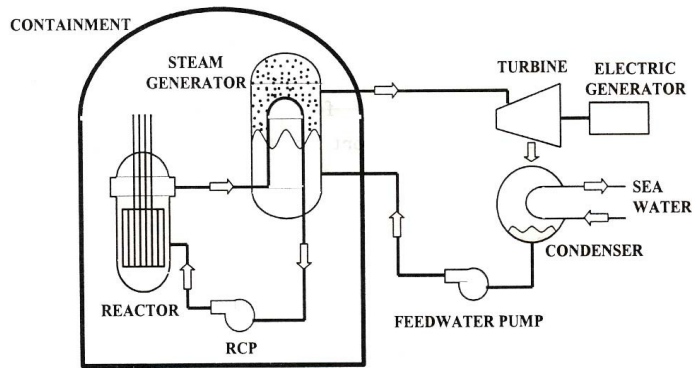
<http://hulk.cesnef.polimi.it/>

<http://www.nuscalepower.com/>

<http://www.hyperionpowergeneration.com/>

http://www.atomicinsights.com/AI_03-20-05.html

<http://www.romawa.nl/nereus/overview.html>



Current nuclear industry

could perhaps double in ~30 years, keeping **6-10% TPES** – not enough!

Issues with nuclear energy

Waste, Proliferation, Safety, Peak Uranium ← not really a problem (IMHO, many differ)

Costs, Scalability, Sustainability ← issues to be addressed

Waste – (partially) spent nuclear fuel (SNF)

Low volume & solid → easy to store separated from biosphere

Zero casualties from all commercial SNF storage

Resource for next generation nuclear power, and rare materials (Tc, Ru, Rh, Pd)

Safety – long term established track record

US nuclear industry is safer than working in financial industry

Actually fission is the safest energy resource ever, in terms of both relative and absolute casualties

Engineered “defense in depth” - adds complexity and expenses

Proliferation – a non issue for civilian nuclear energy

Using materials from civilian cycle is harder than to start from scratch, besides security issues heavy shielding, remote machining, rad damage to electronics, RG-Pu – 11.2 W/kg heat, “150W bulb wrapped by explosives...”

<http://enochthered.wordpress.com/2009/03/02/nuclear-power-and-terrorist-proliferation-of-nuclear-weapons/>

Home made nukes impossible – requires easily detectable industry

States which desire nuclear armament follow long time established, well documented routes directly to weapon grade materials, several designs available including warheads

Apparently replication of these 60 years old processes is rather simple, as demonstrated in 2006 by isolated & starving North Korea http://en.wikipedia.org/wiki/2006_North_Korean_nuclear_test

=> **nuclear weapon proliferation is an issue for international politics**

Nuclear energy can help with quality of life, thus decreasing societal tension in regions.

Appropriate regulations of nuclear materials and safety necessary for the above

However, nuclear regulators task: minimizing risks from nuclear energy; without considering the risks of not using nuclear energy => stagnation

How much uranium is there?

Log-normal uranium distribution

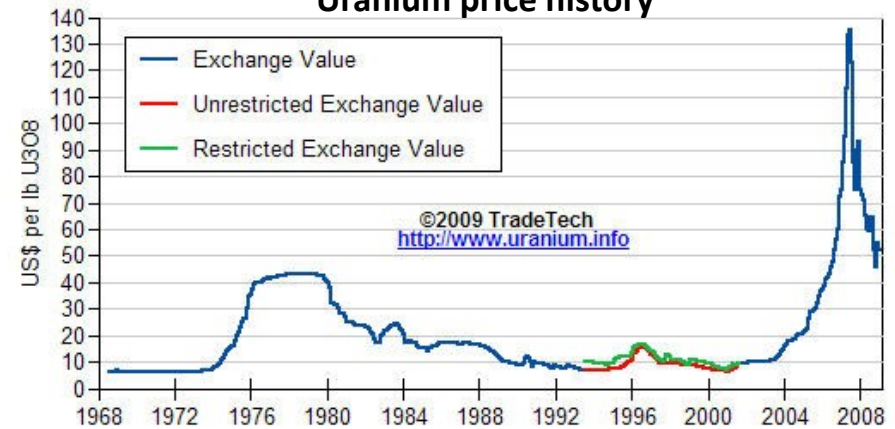
type of deposit	estimated tonnes	estimated ppm
Vein deposits	2×10^5	10,000+
Pegmatites, unconformity deposits	2×10^6	2,000-10,000
fossil placers, sand stones	8×10^7	1,000-2,000
lower grade fossil placers, sandstones	1×10^8	200-1,000
volcanic deposits	2×10^9	100-200
black shales	2×10^{10}	20-100
shales, phosphates	8×10^{11}	10-20
granites	2×10^{12}	3-10
average crust	3×10^{13}	1-3
evaporites, siliceous ooze, chert	6×10^{12}	.2-1
oceanic igneous crust	8×10^{11}	.1-.2
ocean water	2×10^{10}	.0002-.001
fresh water	2×10^6	.0001-.001

Currently known and estimated uranium resources cheaper than \$130/lb enough for ~80 years at current consumption.

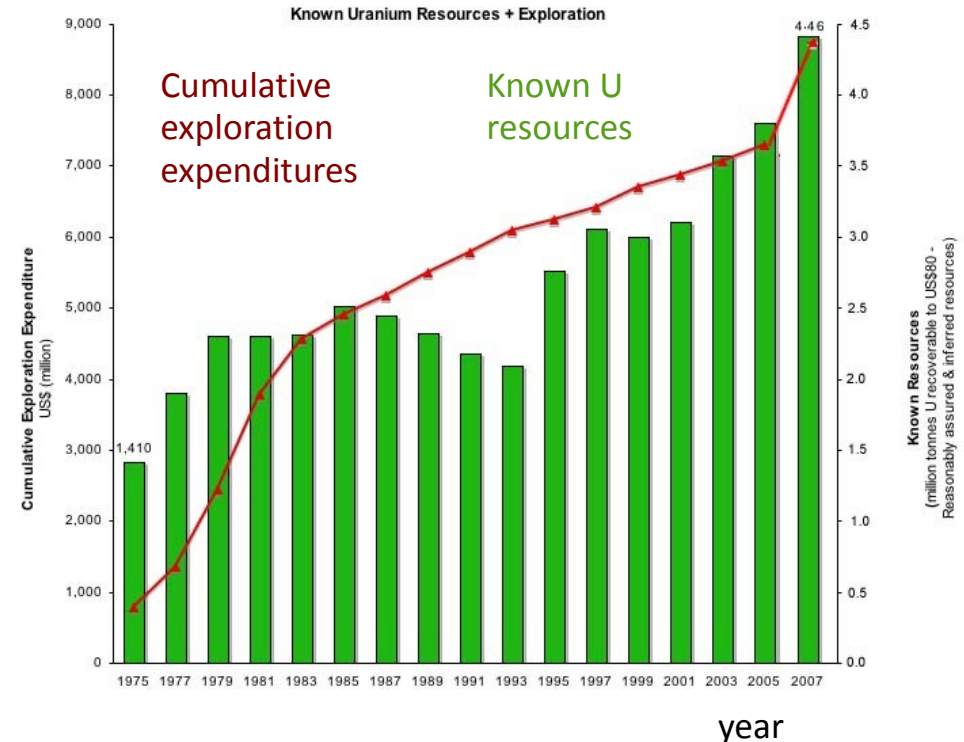
References:

<http://www.world-nuclear.org/info/inf75.html>
<http://nuclearinfo.net/Nuclearpower/UraniumDistribution>
 IAEA, Uranium 2007: <http://books.google.com/books?id=ABKo3wSTvt0C>
http://www-pub.iaea.org/MTCD/publications/PDF/te_1033_prn.pdf
http://www.energywatchgroup.org/fileadmin/global/pdf/EWG_Report_Uranium_3-12-2006ms.pdf
http://nuclearinfo.net/Nuclearpower/WebHomeEnergyLifecycleOfNuclear_Power
<http://www.world-nuclear.org/info/inf11.html>

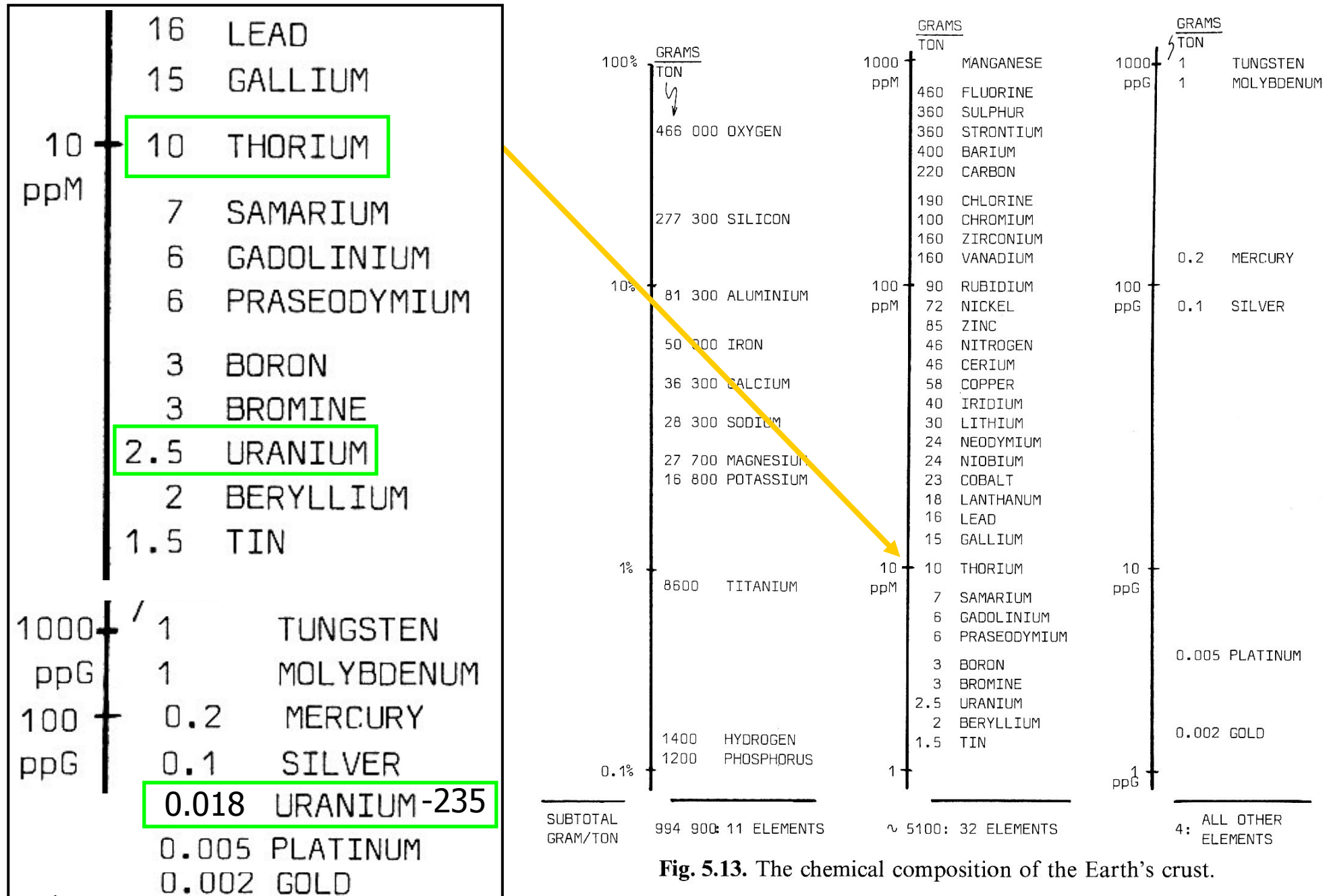
Uranium price history



Recently used mineral, not fully prospected



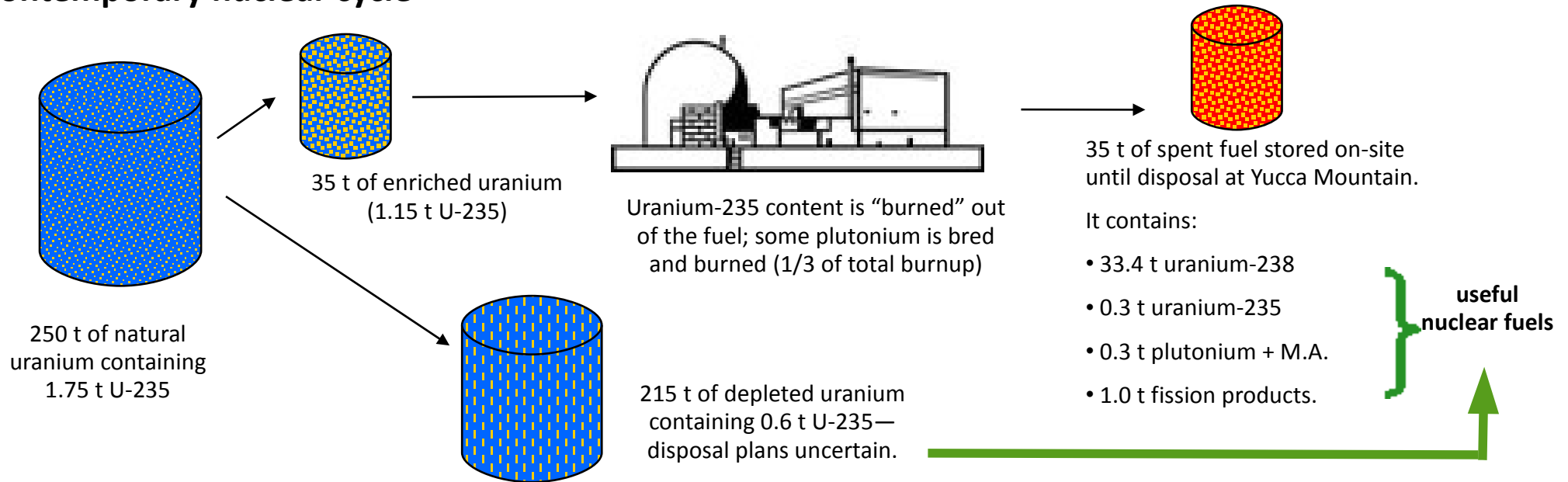
Thorium and Uranium Abundant in the Earth's Crust



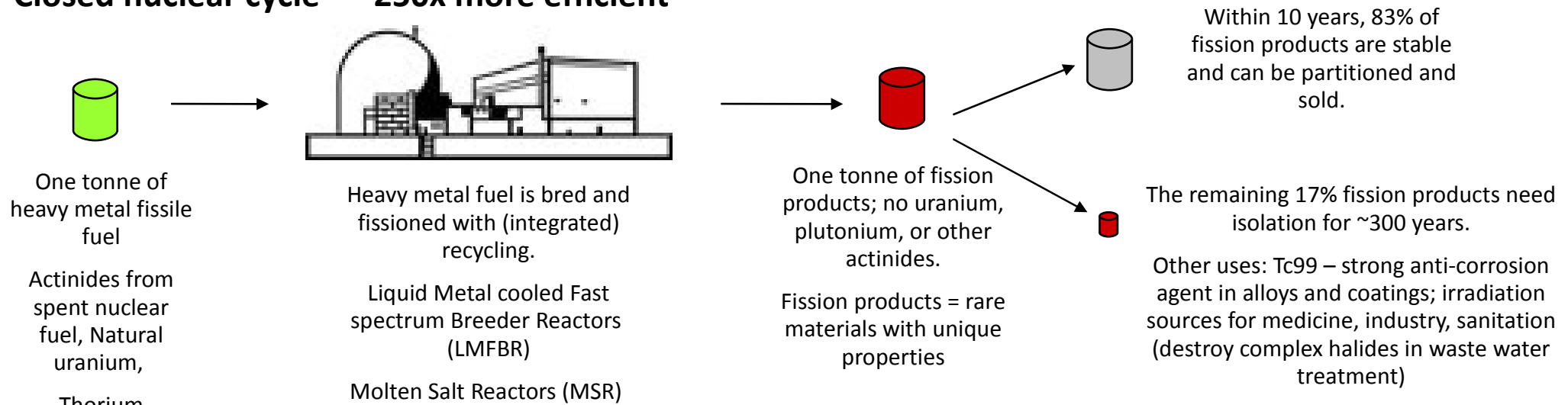
Nuclear fuel cycles

mission: make 1000 MW of electricity for one year

Contemporary nuclear cycle



Closed nuclear cycle – ~250x more efficient



Fast breeder reactors (LMFBR)

Originally much less uranium resources known → (net) breeding essential

<http://en.wikipedia.org/wiki/EBR-I>

1951 – EBR1 near Arco, Idaho, first electricity from fission (Dec 22)

1953 – net breeding experimentally confirmed

~20 FBRs built, ~300 reactors years of experience, 3 operating

US. research (Integral Fast Reactor, IFR) killed in 1994,
some revival by GNEP (GE-Hitachi PRISM, metallic fuel,
integrated proliferation resistant pyro-processing)

French research (Superphenix → EFR) killed by politics in 1996

Development in Russia, India, Japan, South Korea, Italy



Advantages: Unlimited fuel supply, Operation close to atmospheric pressure, Passive safety demonstrated during IFR development, little R&D needed

Disadvantages: High fissile load (12 t for Na, 20 t for Pb coolant for 1GWe) – can only start <100 reactors, Not that high temperature for direct heat utilization (550 C = 1022 F), Public Perception, Net breeding (used to be advantage) may be problematic, Cost?

Fast reactor summary references:

<http://www.world-nuclear.org/info/inf98.html>

<http://www.world-nuclear.org/info/inf08.html>

Integral Fast Reactor links:

<http://www.prescriptionfortheplanet.com/> ← **recommended book**

<http://bravenewclimate.com/2009/02/12/integral-fast-reactors-for-the-masses/>

<http://skirsch.com/politics/globalwarming/ifr.htm>

April 20 2009

Uranium resource with closed cycle:

<http://www-formal.stanford.edu/jmc/progress/cohen.html>

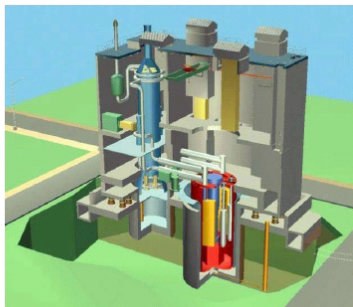
<http://sustainablenuclear.org/PADs/pad11983cohen.pdf>

SuperPhenix

<http://en.wikipedia.org/wiki/Superph%C3%A9nix>

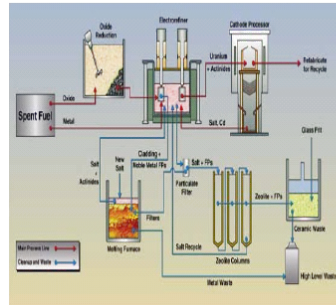
<http://lpsc.in2p3.fr/gpr/sfp/superphenix.html>

PRISM



- + 840 MWth & 311 MWe
- + Na cooled fast reactor
- + Passive safety
- + Modular/scalable
- + Factory built
- + Flexible fuel cycle (broad input composition)
- + Metal or oxide fuel (metal pref.)
- + Extensive component testing

Electro Refining



- + Modular/scalable
- + Sized to support ABR
- + Proliferation resistant
- + Removal of volatile FP through voloxidation
- + Continuous or batch process
- + Extensive testing in the U.S., Russia, Japan, and Korea
- + Used by industrial refiners

GE-Hitachi PRISM

IFR++ revised under GNEP

Metallic fuel: Zr-U-Pu alloy

Integrated fuel cycle: fuel pins melted, electro-refined (FPs separated from useful nuclear fuels), re-casted, re-used

Proliferation resistant – no Pu separation

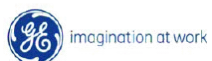
GE: “Advanced Recycling Centers” (ARC)
burn SNF, WG-Pu, DU

26 ARCs consume 120K t SNF

Avoid 400 Mt CO₂/year

Produce 50 GWe @ \$46/MWhe

Timeline: within 5-15 years fuel qualification program with a test reactor



NRC's NUREG-1368 Concluded

- No obvious impediments to licensing the PRISM (ALMR) design have been identified
- There are eight design features that deviated from LWRs
 - accident evaluation
 - calculation of source term
 - containment
 - emergency planning
 - staffing
 - heat removal
 - positive void
 - control room design



GE-Hitachi slides:

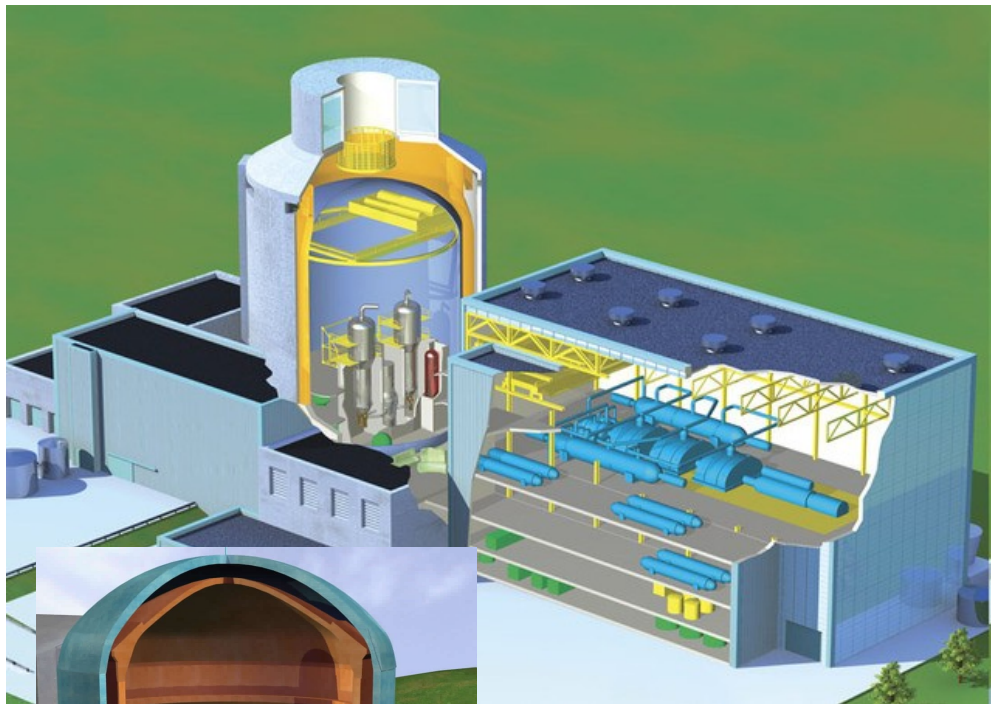
<http://local.ans.org/virginia/meetings/2007/2007RIC.GE.NRC.PRISM.pdf>
<http://www.energyfromthorium.com/gnep/GE-Hitachi%20Presentation.ppt>

NUREG-1368:

http://www.osti.gov/bridge/product.biblio.jsp?osti_id=10133164

PWR vs. LMFBR comparison

Pressurized Water Reactor (PWR) Westinghouse AP1000



Areva EPR (PWR)



LMFBR

GE-Hitachi PRISM

(turbine and generator not shown)

No steam expander and condenser
No huge containment needed
Reactor and fuel electro-refining
small enough for underground location

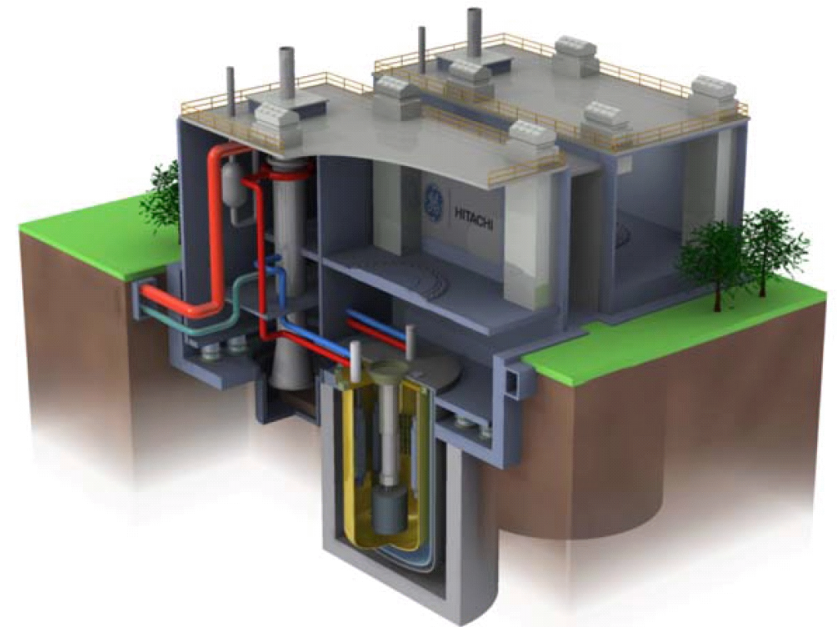
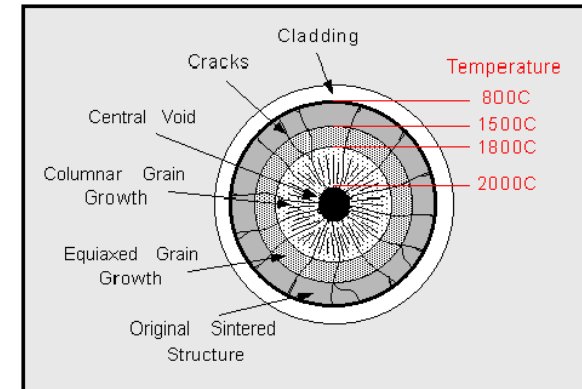


Figure 2: PRISM Reactor power block used to produce electricity from spent nuclear fuel.

Can we do better? Goal: Cheaper than coal!

Solid fuels – deformations (swelling) & accumulation of fission products (degradation of solid fuel matrix, neutron poisons) **limit achievable burn-up**
Expensive fuel manufacturing, burnable poisons, excess reactivity to compensate short term FPs, shutdowns for fuel rotation necessary. Waste, reprocessing.



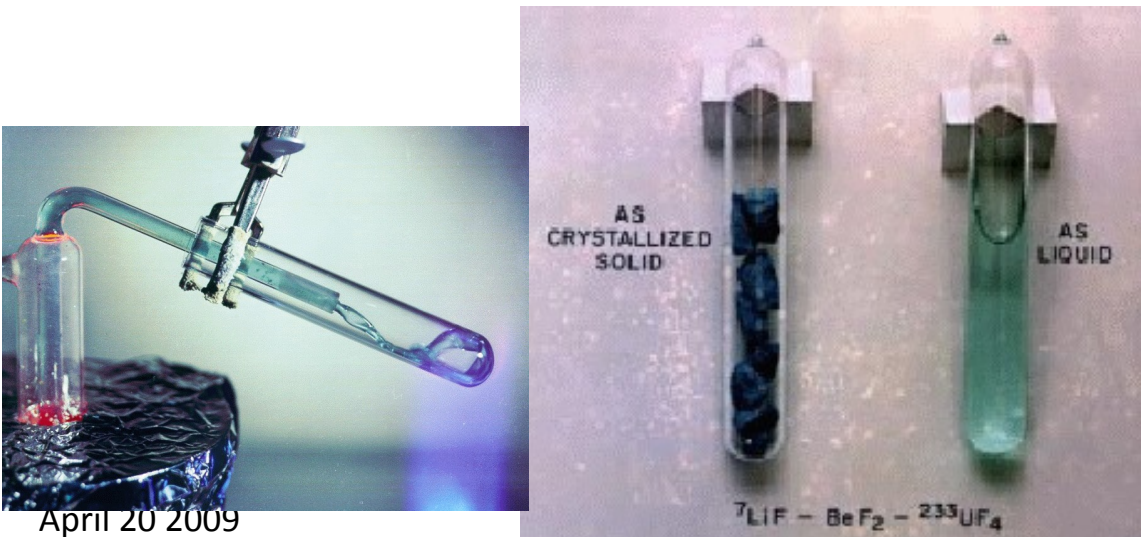
Fluid fuels, in particular **molten fluoride salts** – ionic bonds; Thorium

The birth of the Liquid Fluoride Reactor

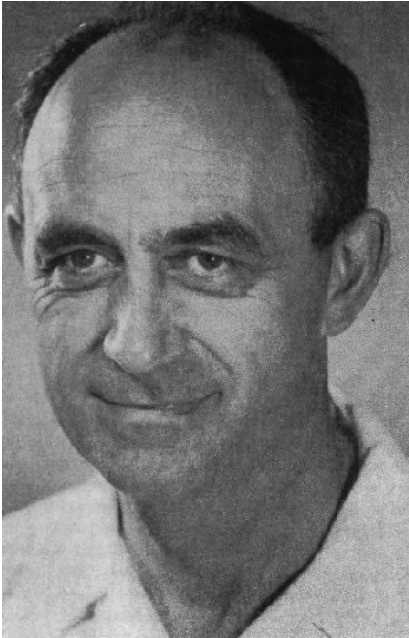
The liquid-fluoride nuclear reactor was invented by Ed Bettis and Ray Briant of ORNL in 1950 to meet the unique needs of the Aircraft Nuclear Program.

Fluorides of the alkali metals were used as the solvent into which fluorides of uranium and thorium were dissolved. In liquid form, the salt had some **extraordinary properties!**

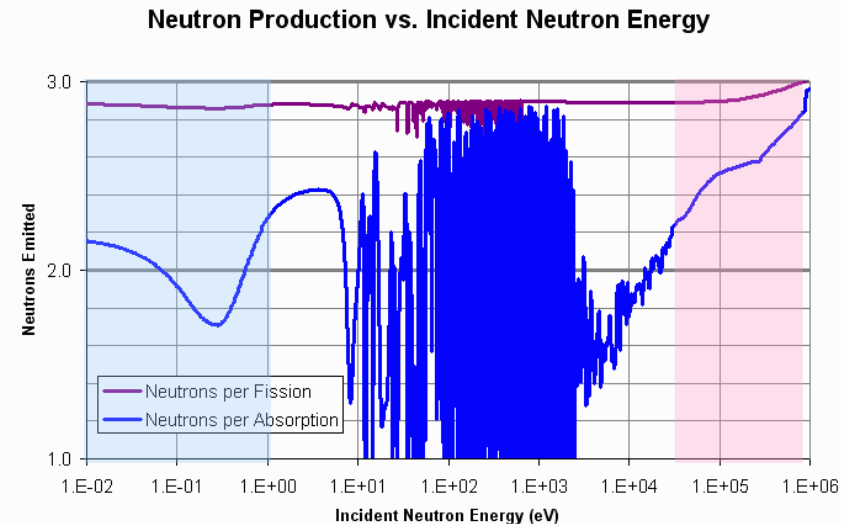
- **Very high negative reactivity coefficient**
 - Hot salt expands and becomes less critical
 - Reactor power would follow the load (the aircraft engine) without the use of control rods!
- **Salts were stable at high temperature**
 - Electronegative fluorine and electropositive alkali metals formed salts that were exceptionally stable
 - Low vapor pressure at high temperature
 - Salts were resistant to radiolytic decomposition
 - Did not corrode or oxidize reactor structures
- **Salts were easy to pump, cool, and process**
 - Chemical reprocessing was much easier in fluid form
 - Poison buildup reduced, breeding enhanced
 - "A pot, a pipe, and a pump..."
 - Whole new landscape of possible reactor geometries



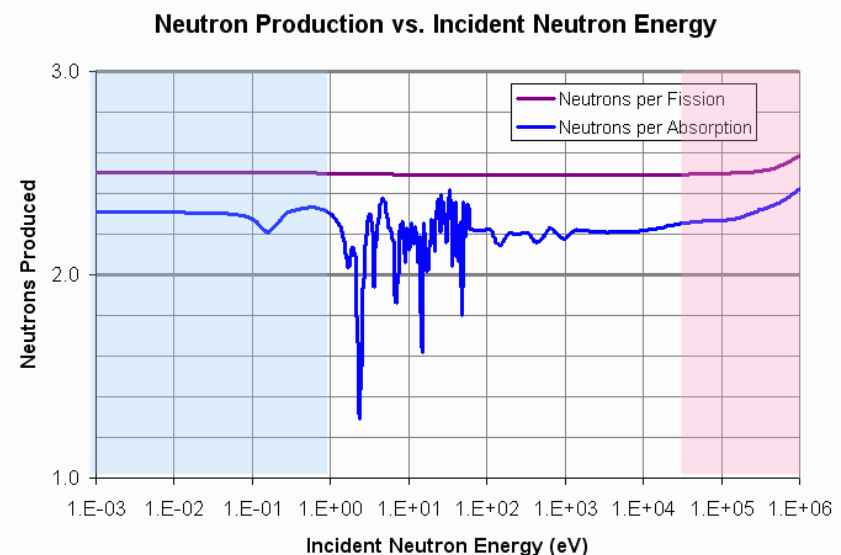
1944: A tale of two isotopes...



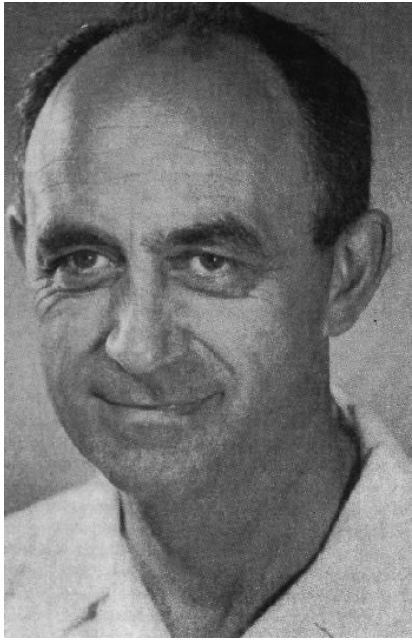
- ◆ Enrico Fermi argued for a program of fast-breeder reactors using uranium-238 as the fertile material and plutonium-239 as the fissile material.
- ◆ His argument was based on the breeding ratio of Pu-239 at fast neutron energies.
- ◆ Argonne National Lab followed Fermi's path and built the EBR-I and EBR-II (IFR).



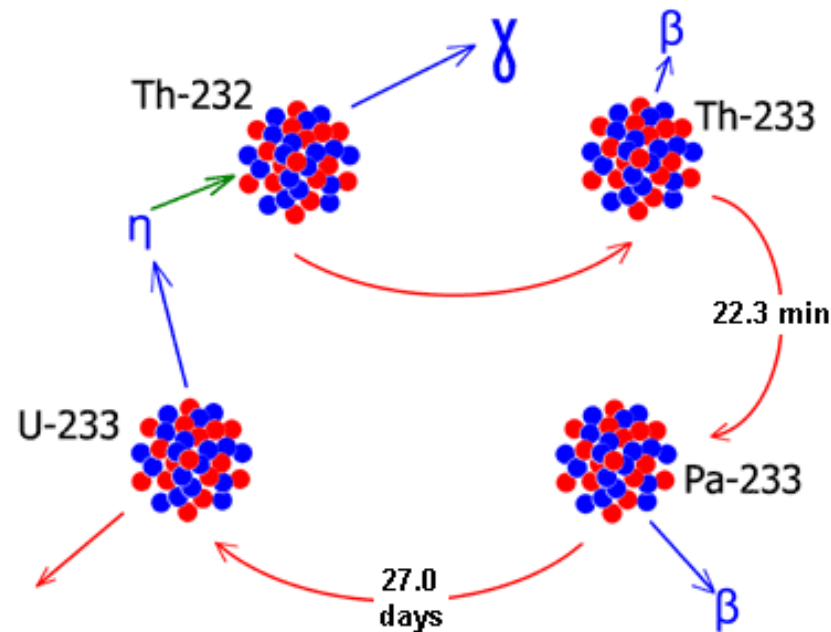
- ◆ Eugene Wigner argued for a thermal-breeder program using thorium as the fertile material and U-233 as the fissile material.
- ◆ Although large breeding gains were not possible, thermal spectrum breeding was possible, with advantages
- ◆ Wigner's protégé, Alvin Weinberg, followed Wigner's path at the Oak Ridge National Lab.



1944: A tale of two isotopes...



“But Eugene, how will you reprocess the thorium fuel effectively?”



Thorium Fuel Cycle



“We’ll build a fluid-fueled reactor, that’s how...”

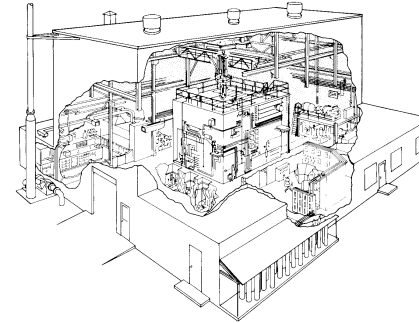
ORNL Fluid-Fueled Thorium Reactor Progress (1947-1960)



1947 – Eugene Wigner proposes a fluid-fueled thorium reactor



1950 – Alvin Weinberg becomes ORNL director



1952 – Homogeneous Reactor Experiment (HRE-1) built and operated successfully (100 kWe, 550K)

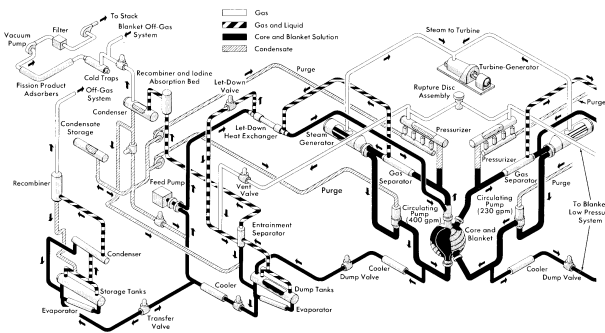
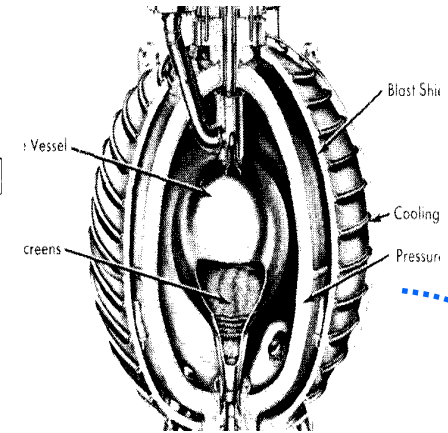
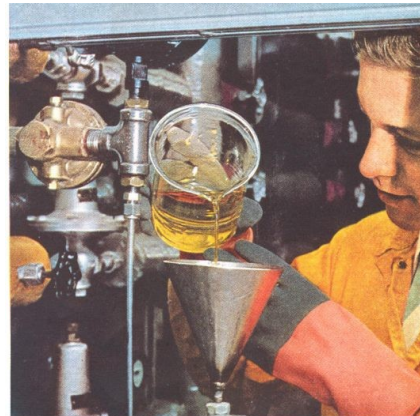


Fig. 7-7. Flowsheet of HRE-2.



1959 – AEC convenes “Fluid Fuels Task Force” to choose between aqueous homogeneous reactor, liquid fluoride, and liquid-metal-fueled reactor. Fluoride reactor is chosen and AHR is canceled

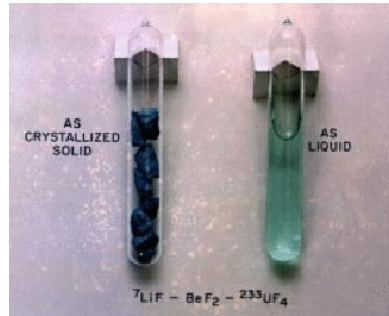
Weinberg attempts to keep both aqueous and fluoride reactor efforts going in parallel but ultimately decides to pursue fluoride reactor.

1958 – Homogeneous Reactor Experiment-2 proposed with 5 MW of power

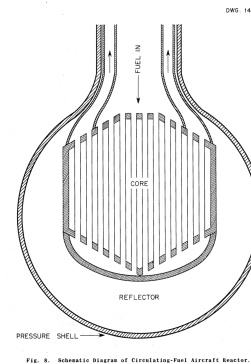
ORNL Aircraft Nuclear Reactor Progress (1949-1960)



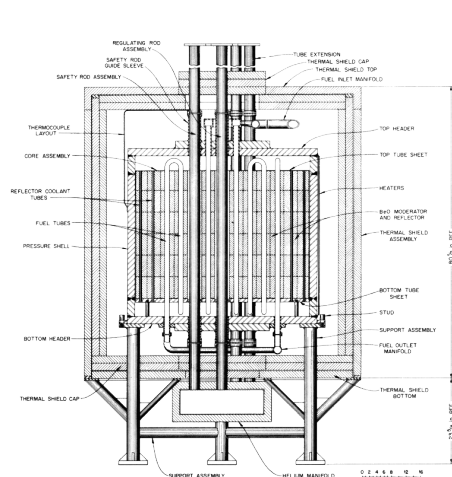
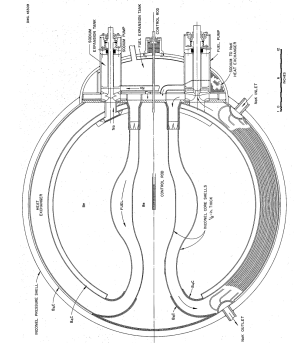
1949 – Nuclear Aircraft Concept formulated



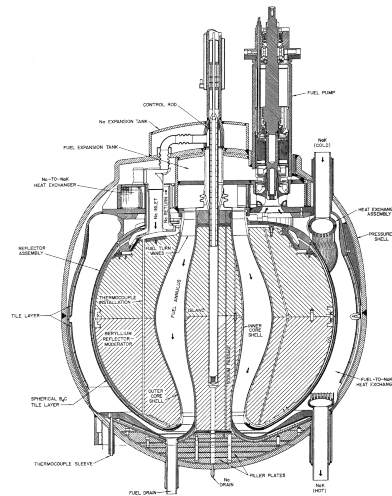
1951 – R.C. Briant proposed Liquid-Fluoride Reactor



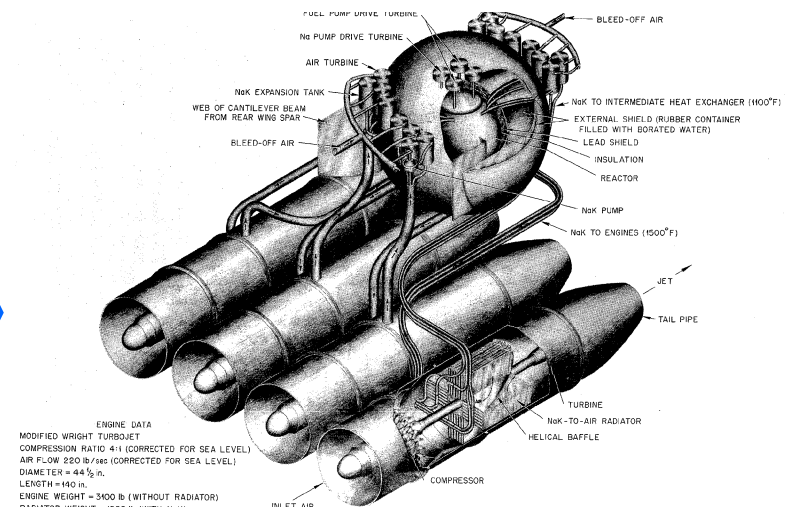
1952, 1953 – Early designs for aircraft fluoride reactor



1954 – Aircraft Reactor Experiment (ARE) built and operated successfully (2500 kWt², 1150K)



1955 – 60 MWt Aircraft Reactor Test (ART, “Fireball”) proposed for aircraft reactor



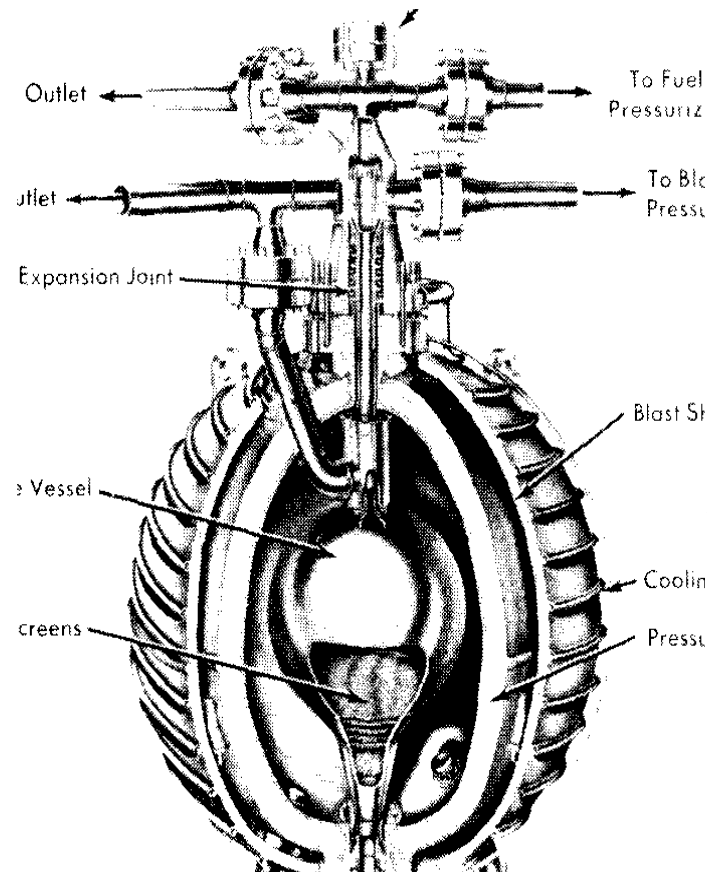
1960 – Nuclear Aircraft Program canceled in favor of ICBMs

Fluid-Fueled Reactors for Thorium Energy

Liquid-Fluoride Reactor (ORNL)

Aqueous Homogenous Reactor (ORNL)

- ♦ Uranyl sulfate dissolved in pressurized heavy water.
- ♦ Thorium oxide in a slurry.
- ♦ Two built and operated.



- ♦ Uranium tetrafluoride dissolved in lithium fluoride/beryllium fluoride.
- ♦ Thorium dissolved as a tetrafluoride.
- ♦ Two built and operated.

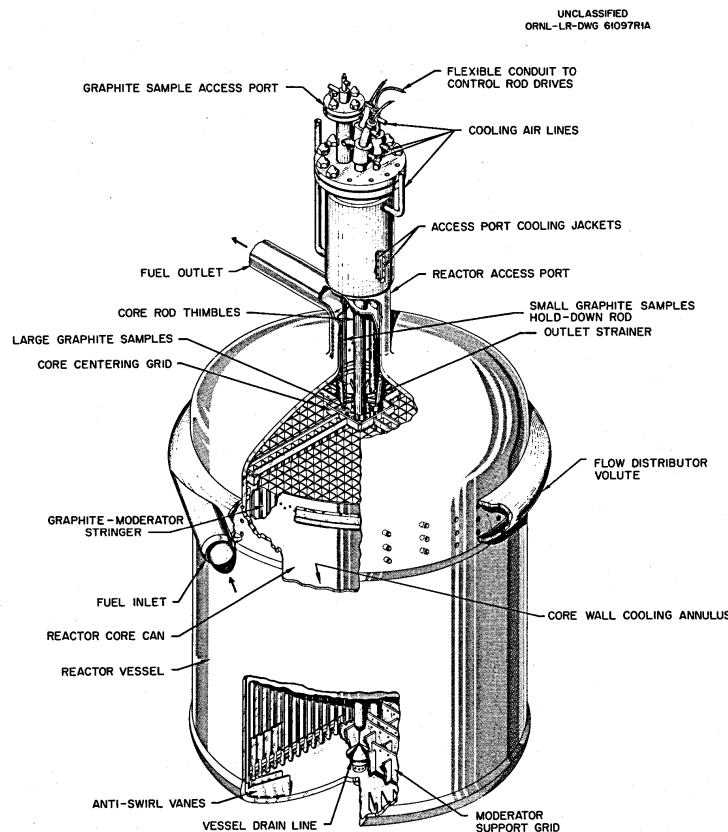
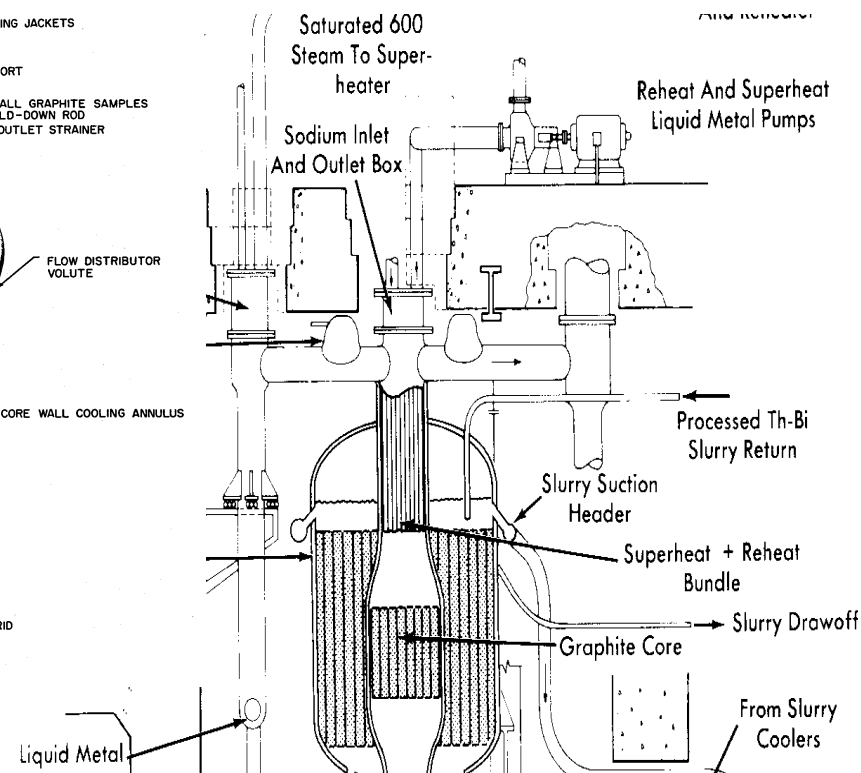


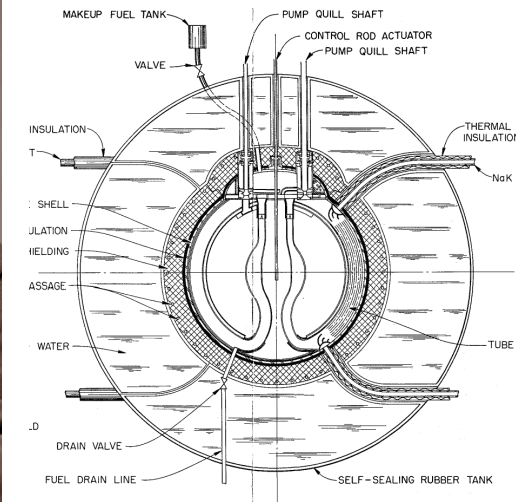
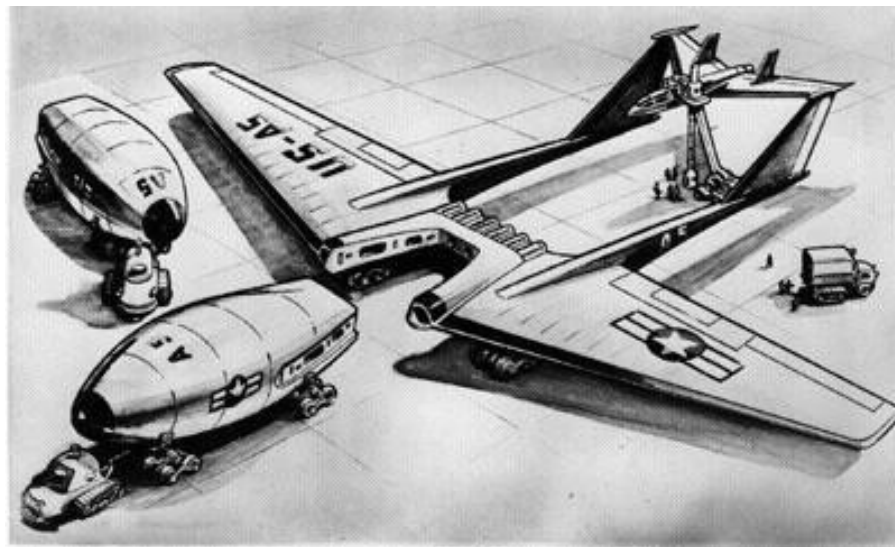
Fig. 6. MSRE Reactor Vessel.

Liquid-Metal Fuel Reactor (BNL)

- ♦ Uranium metal dissolved in bismuth metal.
- ♦ Thorium oxide in a slurry.
- ♦ Conceptual—none built and operated.



Aircraft Nuclear Program allowed ORNL to develop reactors



It wasn't that I had suddenly become converted to a belief in nuclear airplanes. It was rather that this was the only avenue open to ORNL for continuing in reactor development.

That the purpose was unattainable, if not foolish, was not so important:

A high-temperature reactor could be useful for other purposes even if it never propelled an airplane...

—Alvin Weinberg

Molten Salt Reactor Experiment (1965-1969)

MSRE: 8 MW(th)

Designed 1960 – 1964
Start in 1965

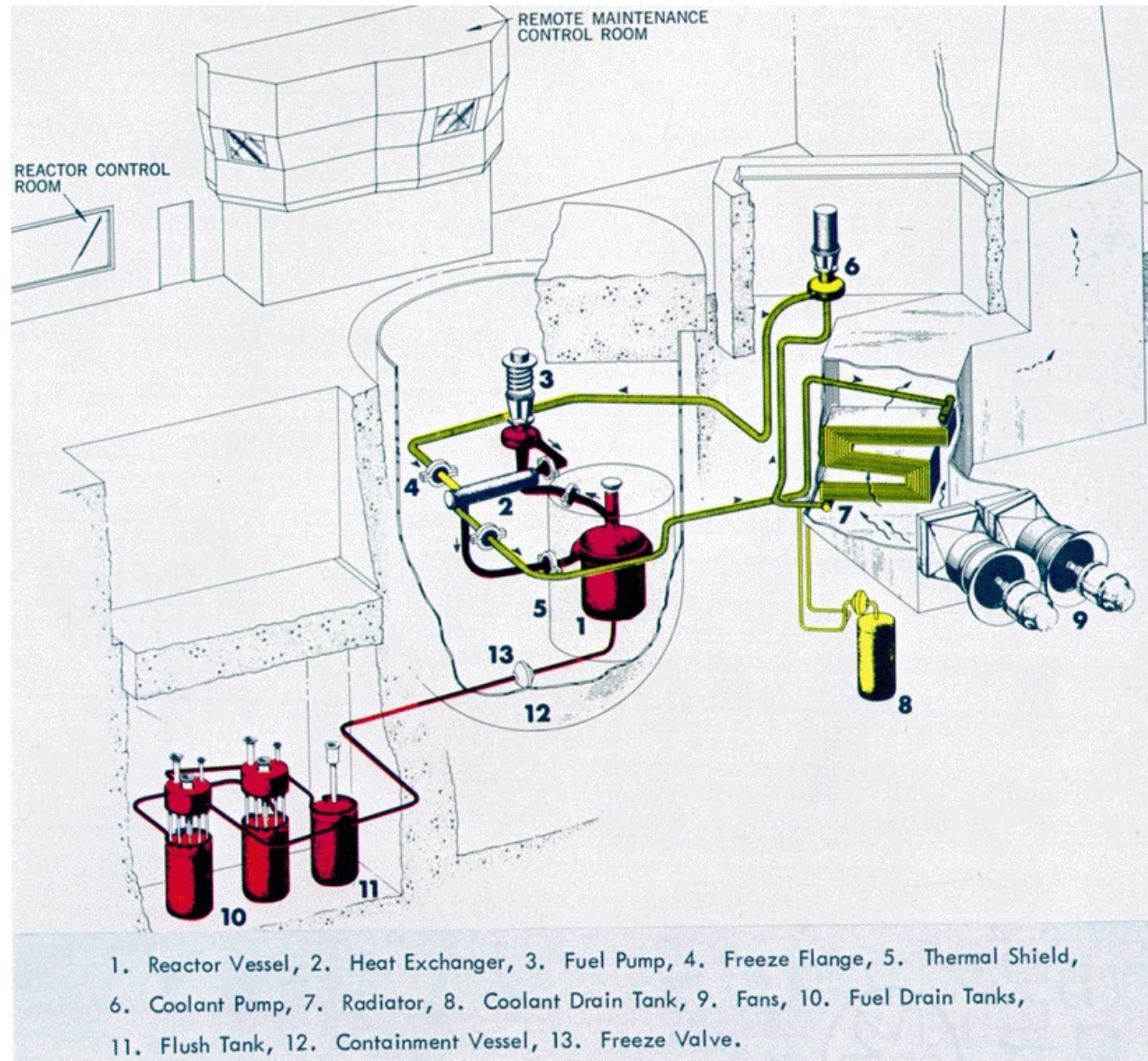
5 years of successful operation

Operated on all 3 fissile fuels
U233, U235, Pu239

Some issues with HastelloyN
found and solved

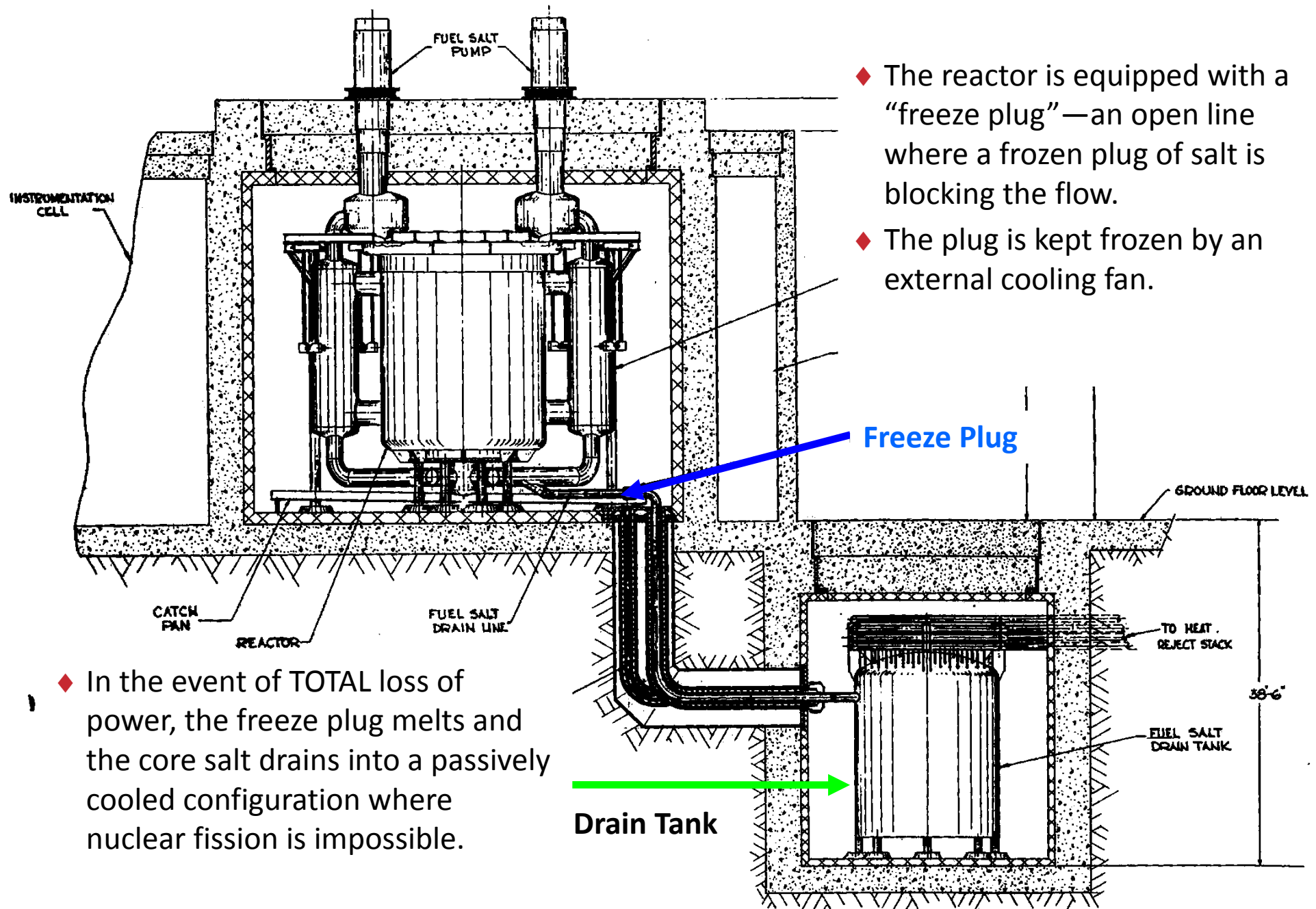
Further designs suggested (MSBE,
MSBR, DMRS), none built

After Alvin Weinberg removed
from ORNL directorate, very little
work done, almost no funding



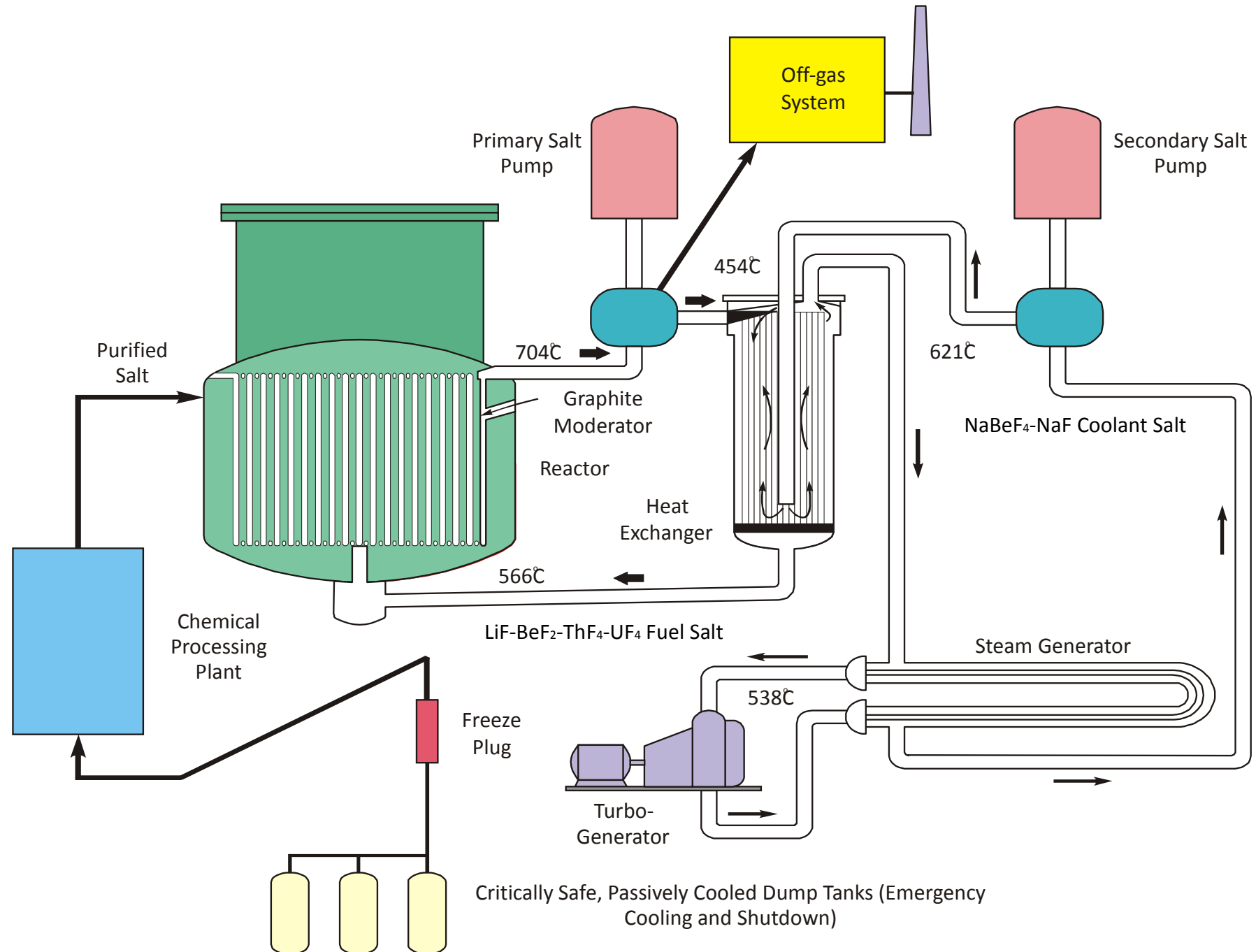
See: http://en.wikipedia.org/wiki/Molten-Salt_Reactor_Experiment

MSR is totally passively safe in case of accident



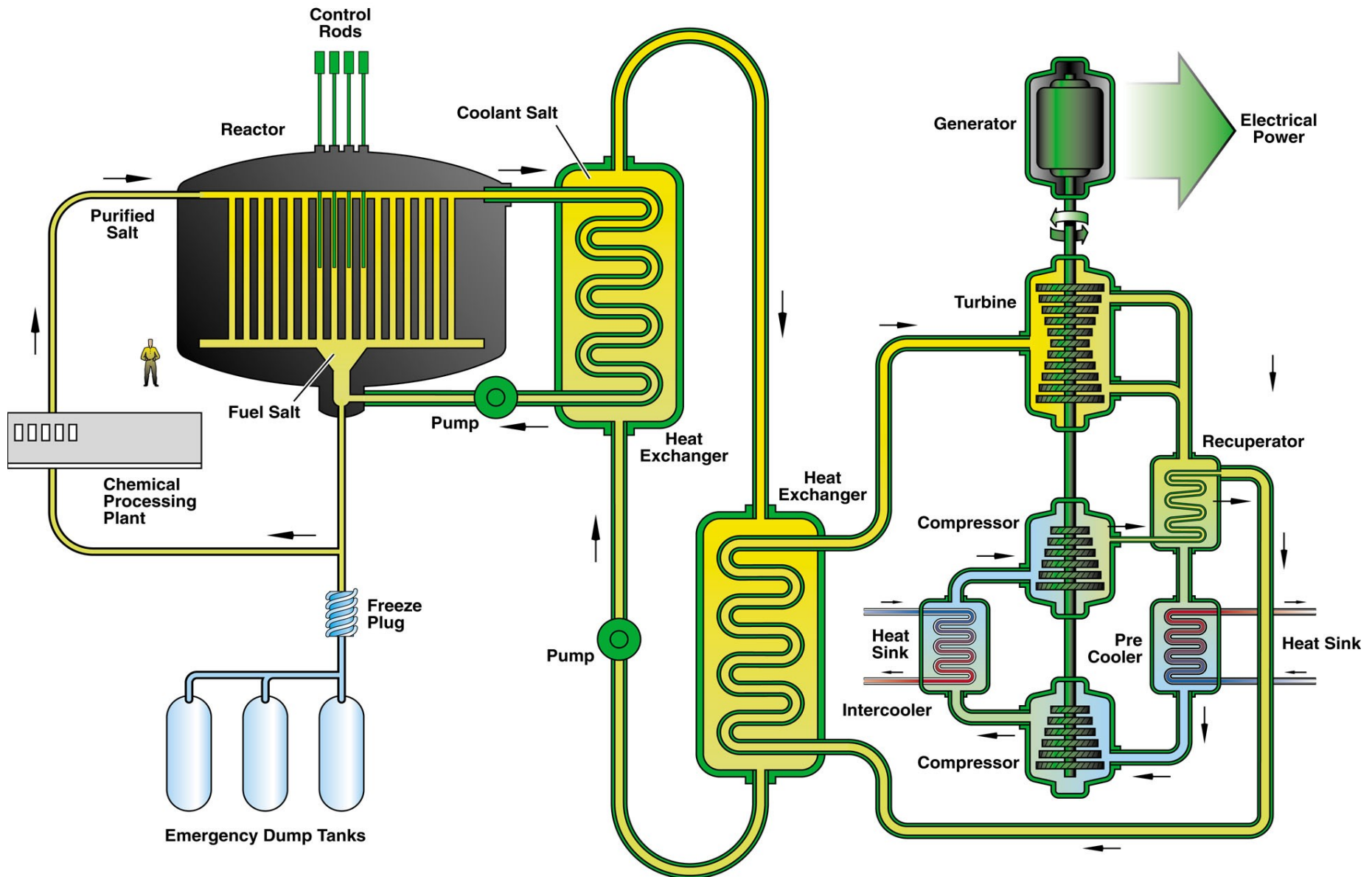
- ◆ In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission is impossible.

1972 Reference Molten-Salt Breeder Reactor Design



A "Modern" Fluoride Reactor

MOOSE



02-GA50807-02

Why the recent interest?

Issues with fossil fuels are getting more and more troubling

Looking for more sustainable but affordable energy resource, high heat for industry

“The second nuclear age”

Several recent advances in key technologies

large scale Brayton cycle heat machines (jet engines, natgas turbines)

more industrial experience with molten salts

material research in fusion energy →

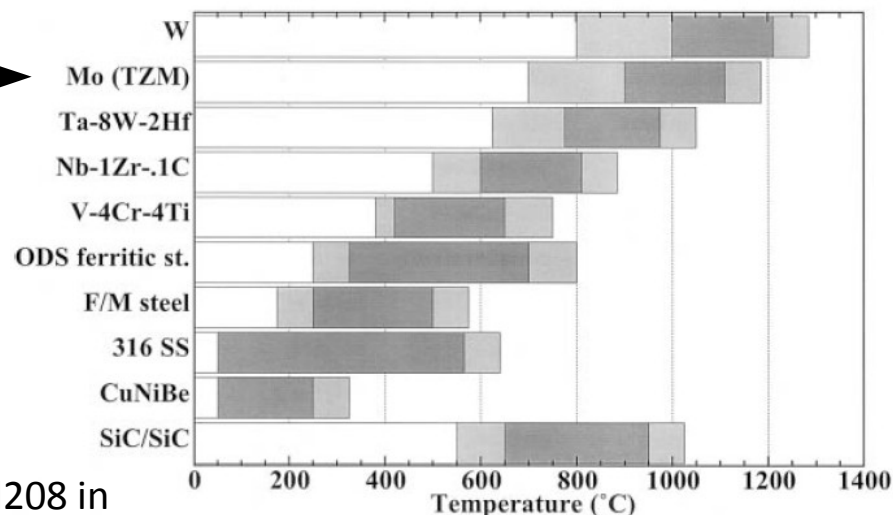
robotic manipulation and control (hot cell operation)

some outstanding issues solved recently

(plumbing problem)

Shift of focus – maximum breeding less important

sustainability, scalability, proliferation resistance



Proliferation resistance – U232 inevitably formed in Th cycle, Tl208 in its decay chain is a strong gamma emitter 2.6MEV

Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

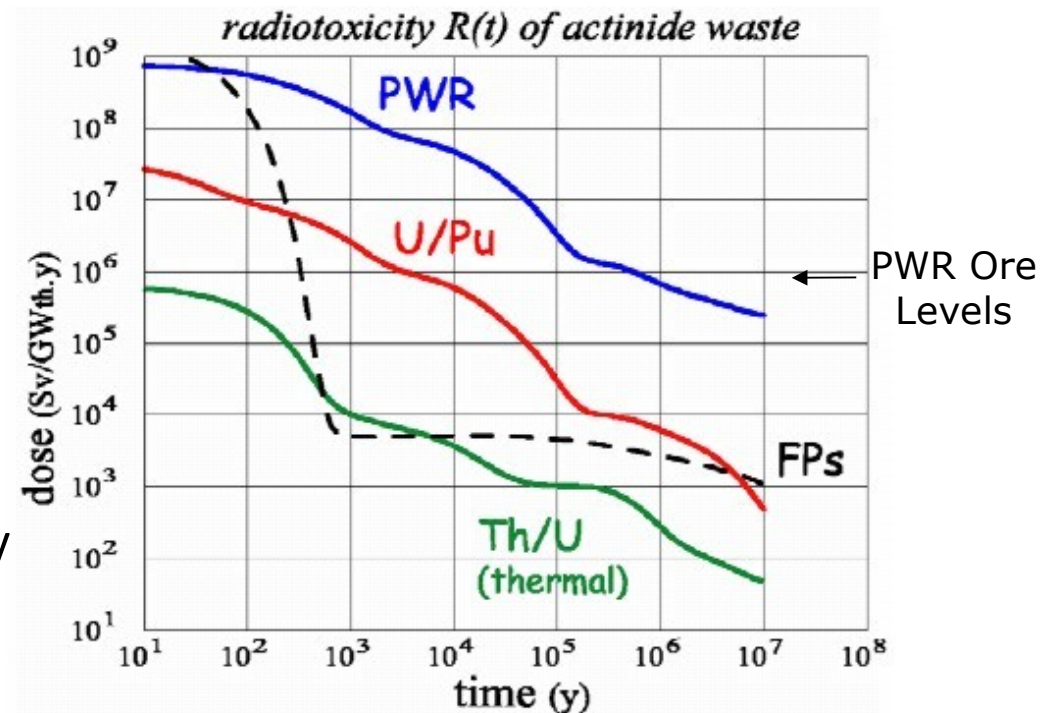
Operating temperature windows (based on radiation amage and thermal creep considerations)

General Benefits of Any Molten Salt Design

Salts are chemically stable, have high boiling point, operate at low pressure
several salt choices, melting points 400-800C, boiling points 1400-1600C
high thermal efficiency (48%), direct use of high temperature heat
Fuel salt at the lowest pressure of the circuit, the opposite of a LWR
Volatile fission products continuously removed and stored, including Xenon.
Control rods or burnable poisons not required so very little excess reactivity
Low fissile inventory
Freeze plug melts upon fuel overheating to drain to critically safe,
passively cooled dump tanks
Ideal for LWR TRU waste destruction
Ability to use closed thorium cycle
Only consume 800 kg thorium per GW/year
Transuranic waste production extremely low
Much lower long term radiotoxicity

Turns waste management
into 500 year job, not nearly
a million year

(taken from David LeBlanc's talk)



Edward Teller promoted MSR to the last month of life

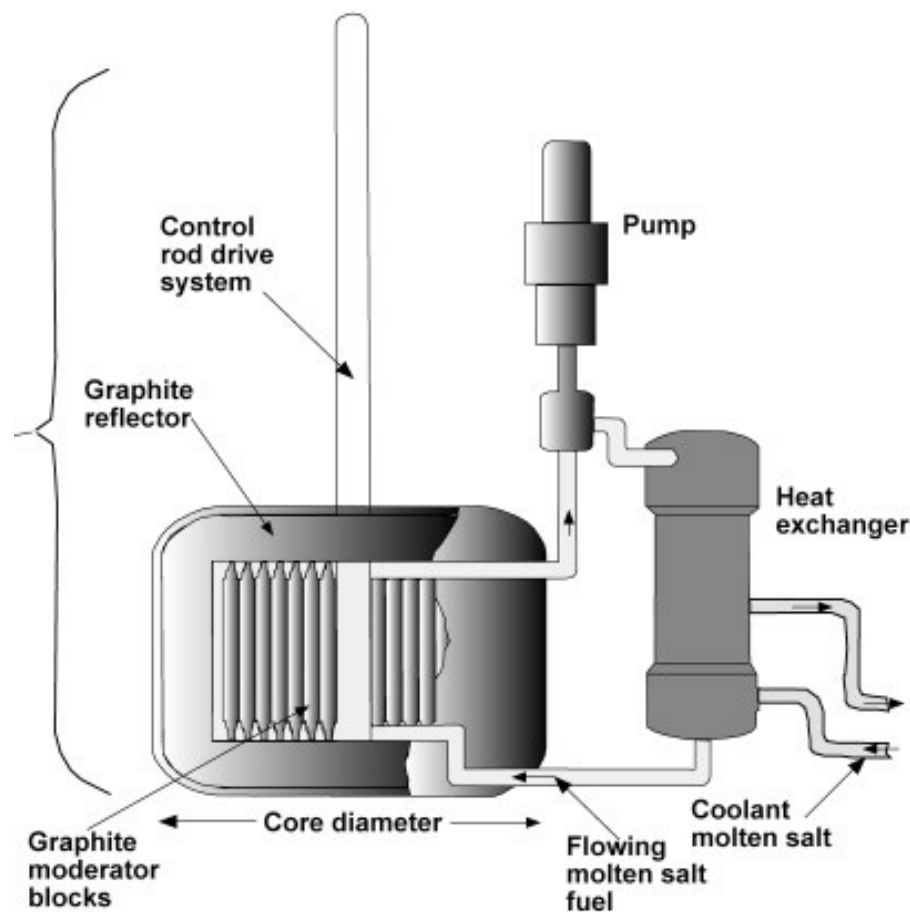


THORIUM-FUELED UNDERGROUND POWER PLANT BASED ON MOLTEN SALT TECHNOLOGY

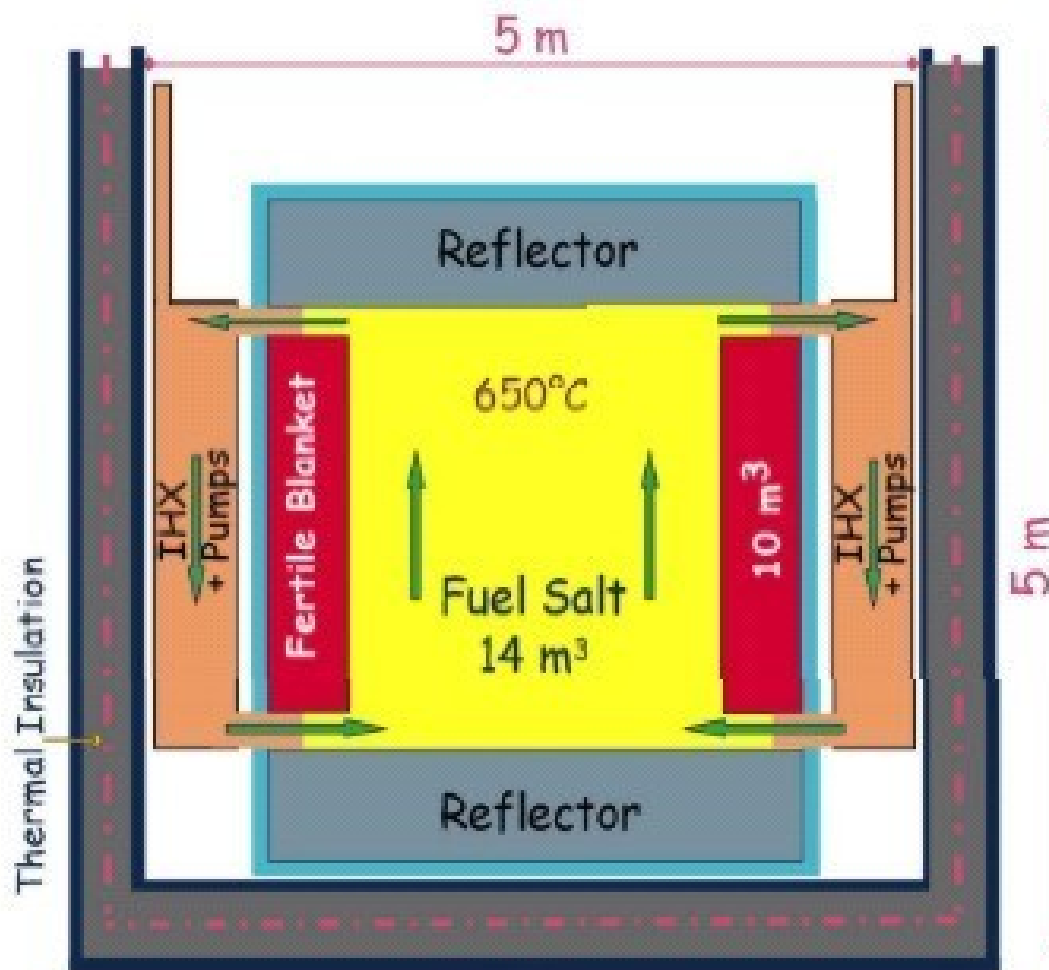
RALPH W. MOIR* and EDWARD TELLER†
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Livermore, California 94551*

Received August 9, 2004
Accepted for Publication December 30, 2004

FISSION REACTORS TECHNICAL NOTE

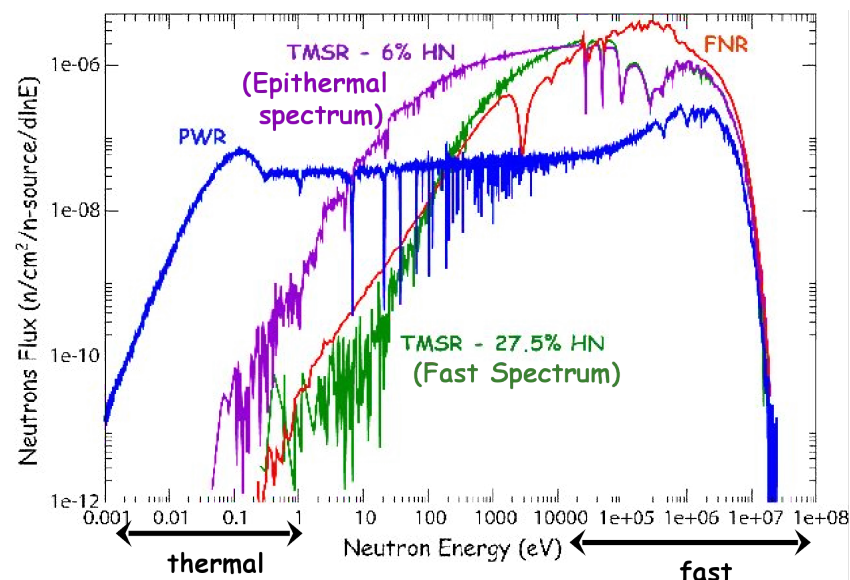


French TMSR: Thorium Molten Salt Reactor



References: <http://tel.archives-ouvertes.fr/docs/00/35/49/37/PDF/HDR-EML-TMSR.pdf>
http://hal.in2p3.fr/docs/00/13/51/41/PDF/ICAPP06_TMSR.pdf
<http://hal.in2p3.fr/docs/00/18/69/44/PDF/TMSR-ENC07.pdf>

Flexibility in neutron spectrum



Schedule

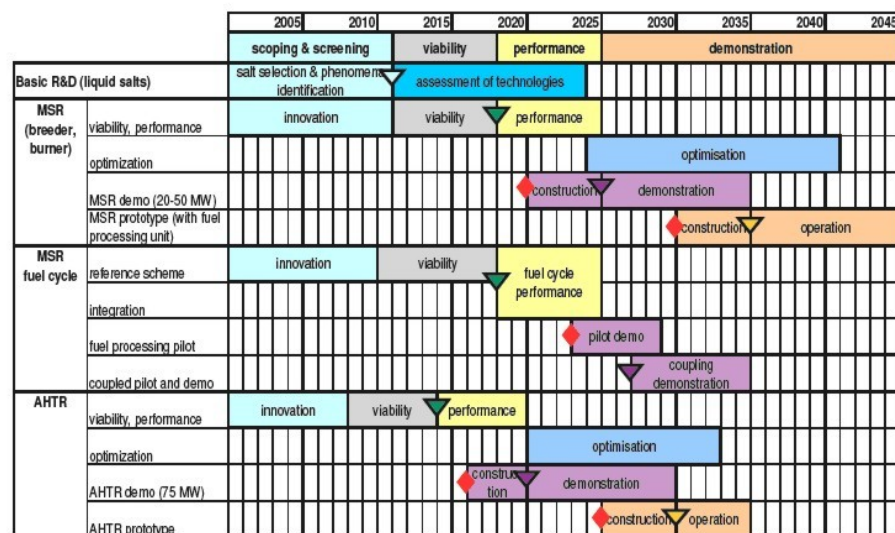
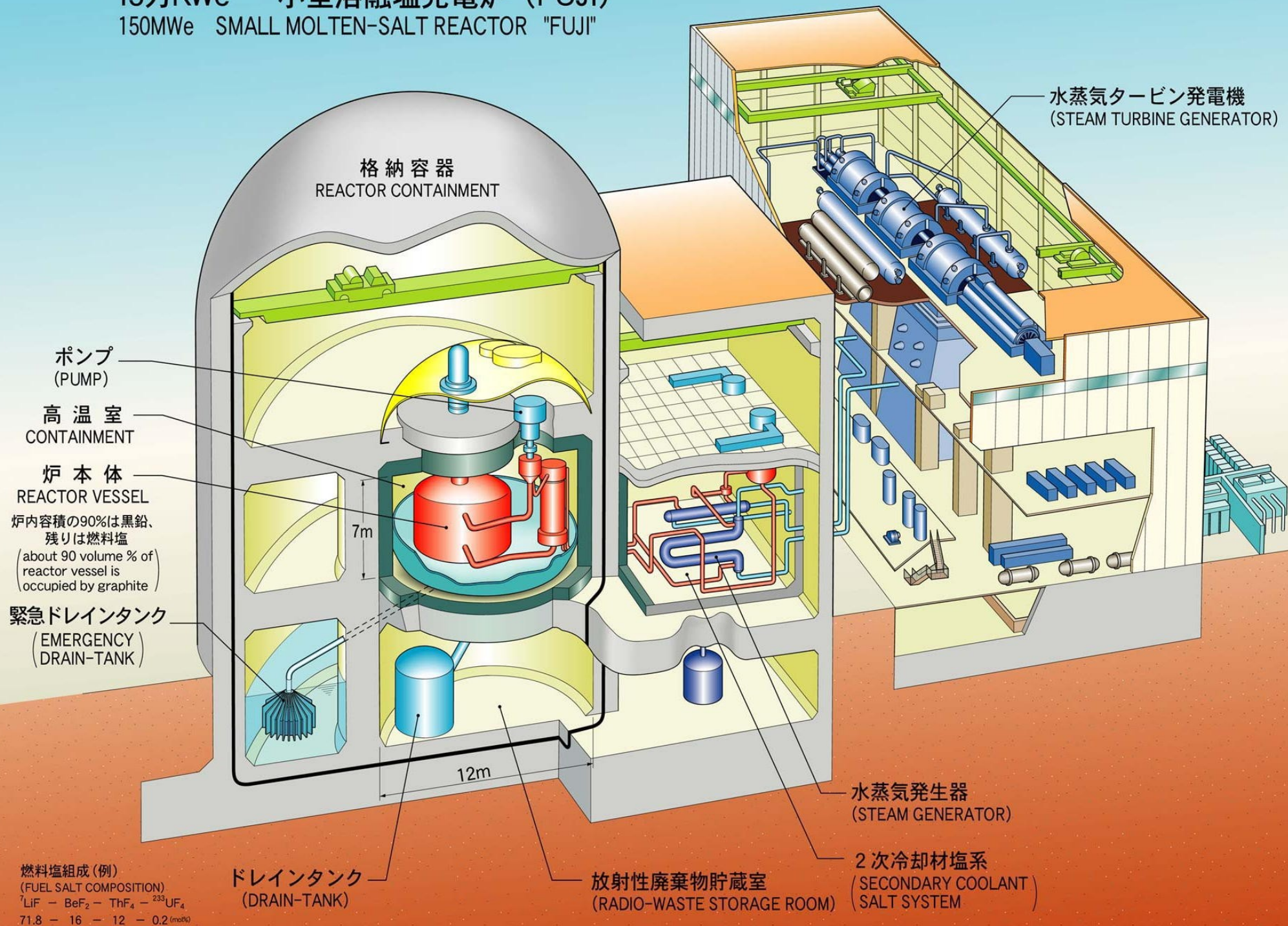


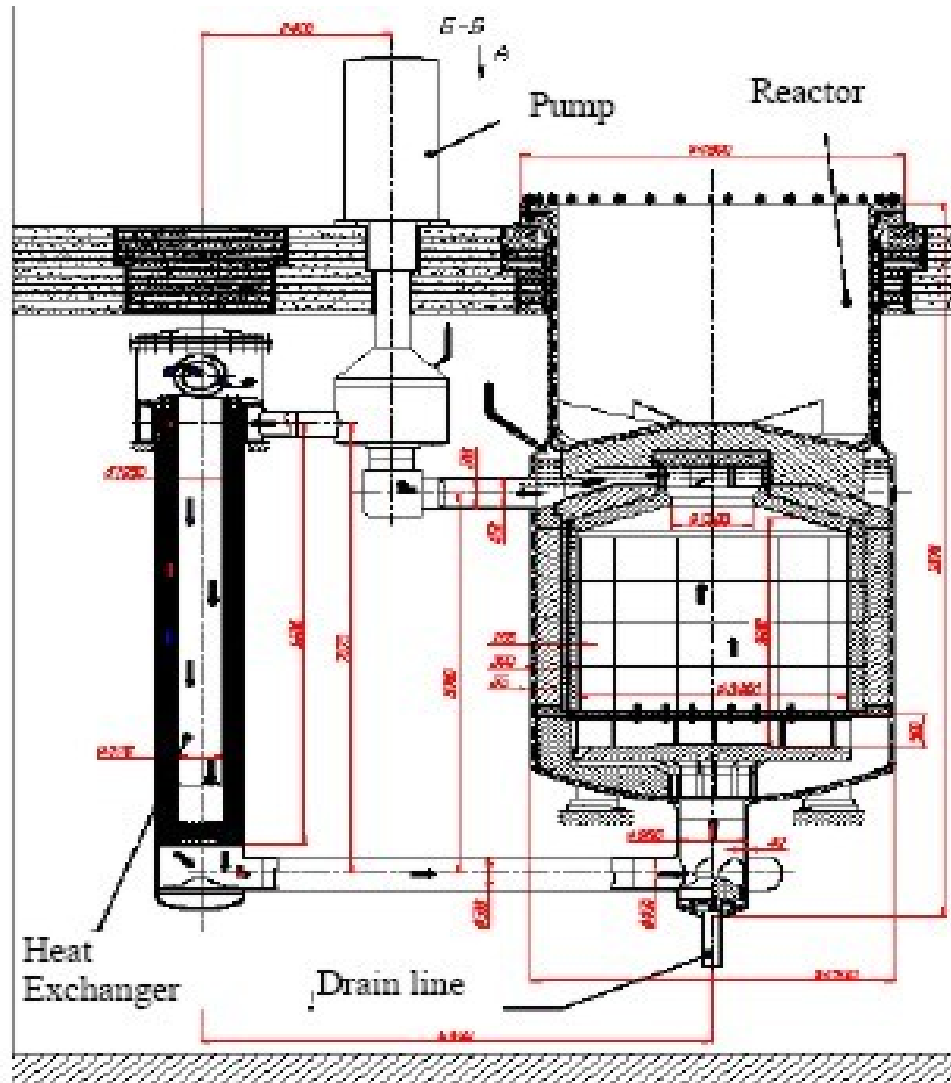
FIG. 1.3 – “Master Plan” du système Réacteurs à Sels Fondus dans le forum International Generation IV [14]

15万KWe 小型溶融塩発電炉 (FUJI)

150MWe SMALL MOLTEN-SALT REACTOR "FUJI"



Russian MOlten Salt Actinide Recycler and Transmuter MOSART



Single fluid, no breeding,
but TRU waste disposal

From: <http://www.torium.se/res/Documents/7548.pdf>

USA – Advanced High Temperature Reactor (AHTR)

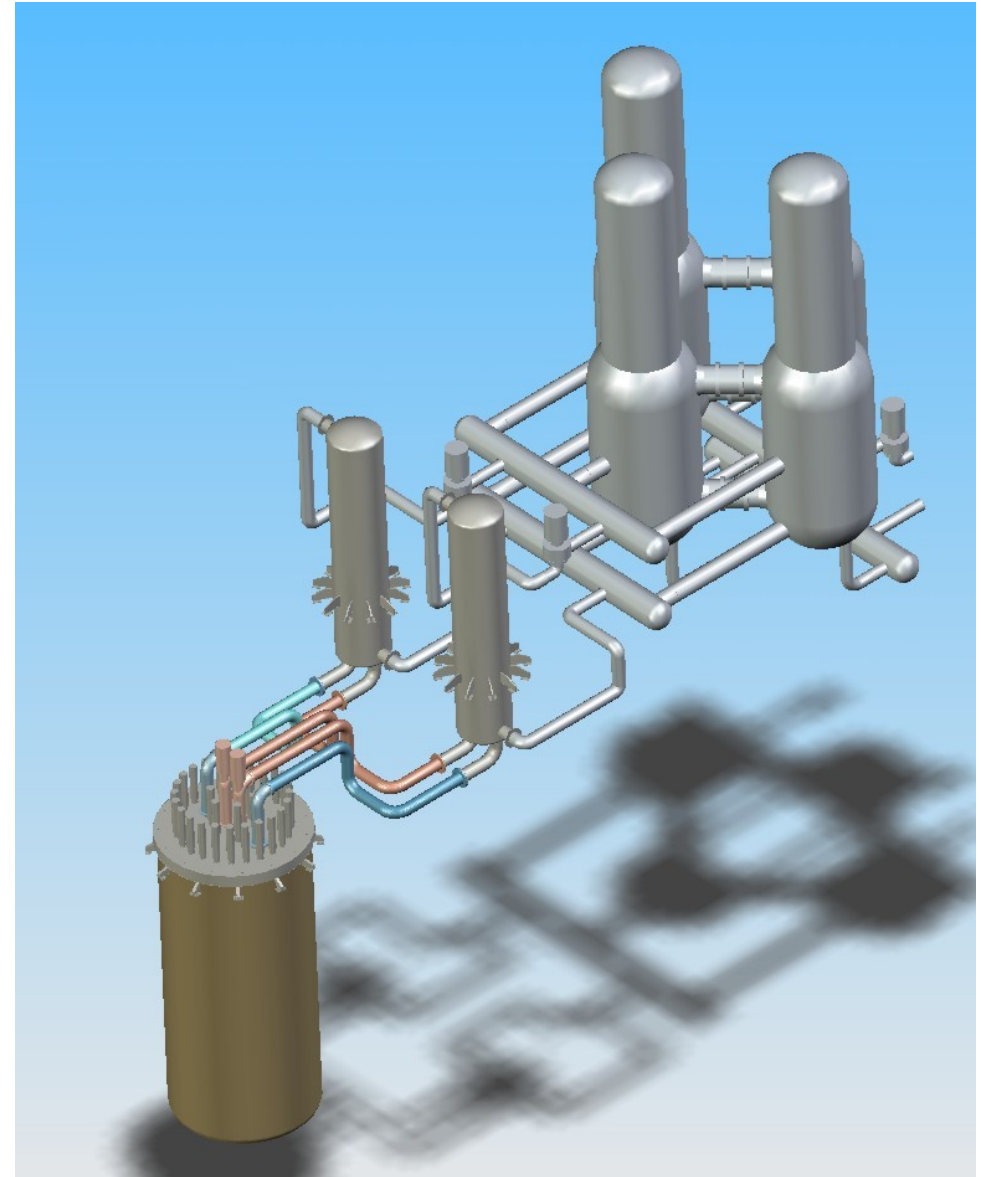
Combination of several “old” technologies

Fluoride salt cooled reactor with TRISO fuel

Brayton cycle turbine

Developed at ORNL and UC Berkeley

See: http://www.discoveret.org/fornl/FORNL_2-15-06.pdf



Thorium MSR (LFTR) produces far less mining waste than a LWR (~4000:1 ratio)

1 GW*yr of electricity from a uranium-fueled light-water reactor



Mining 800,000 t of ore
containing 0.2% uranium
(260 t U)



Generates ~600,000 t of waste rock



Milling and processing to
yellowcake—natural U_3O_8
(248 t U)

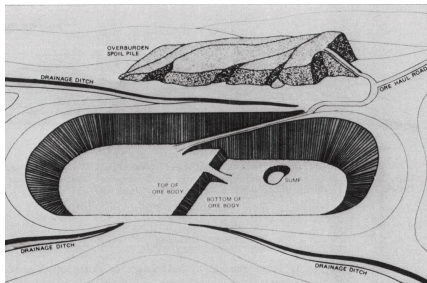
Generates 130,000 t of mill tailings



Conversion to natural UF_6
(247 t U)

Generates 170 t of solid waste
and 1600 m³ of liquid waste

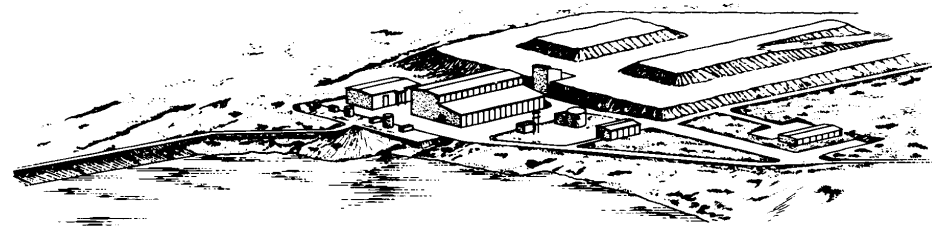
1 GW*yr of electricity from a thorium-fueled liquid-fluoride reactor



Mining 200 t of ore
containing 0.5% thorium
(1 t Th)



Generates ~199 t of waste rock



Milling and processing to thorium nitrate $ThNO_3$ (1 t Th)

Generates 0.1 t of mill tailings and 50 kg of aqueous wastes

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: <http://www.wise-uranium.org/nfcm.html>

Thorium is virtually limitless in availability

- ◆ Thorium is abundant around the world
 - 12 parts-per-million in the Earth's crust
 - India, Australia, Canada, US have large resources.
- ◆ There will be no need to horde or fight over this resource
 - A single mine site at the Lemhi Pass in Idaho could produce 4500 t (metric tonnes) of thorium per year.
 - 2007 US energy consumption = 95 quads = 2580 t of thorium

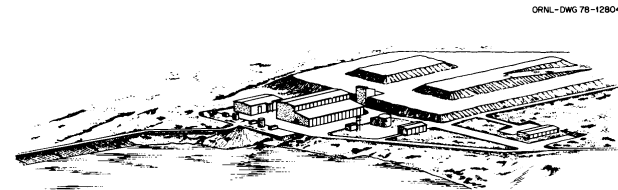
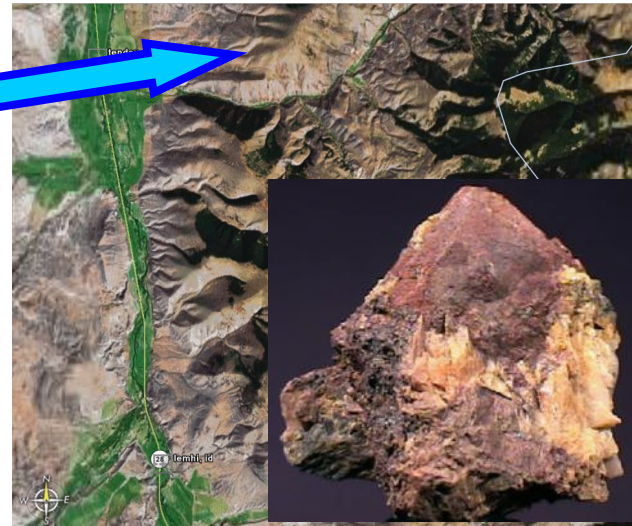


Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from U.S. Nuclear Regulatory Commission, Final Environmental Statement Bear Creek Project, NUREG-0129, Docket No. 40-8452, June 1977.)



The United States has buried 3200 metric tonnes of thorium nitrate in the Nevada desert.

There are 160,000 t of economically extractable thorium in the US, even at today's "worthless" prices!

ANWR times 6 in the Nevada desert



- ◆ Between 1957 and 1964, the Defense National Stockpile Center procured 3215 metric tonnes of thorium from suppliers in France and India.
- ◆ Recently, due to “lack of demand”, they decided to bury this entire inventory at the Nevada Test Site.
- ◆ This thorium is equivalent to 240 quads of energy*, if completely consumed in a liquid-fluoride reactor.

*This is based on an energy release of $\sim 200 \text{ MeV}/232 \text{ amu}$ and complete consumption. This energy can be converted to electricity at $\sim 50\%$ efficiency using a multiple-reheat helium gas turbine; or to hydrogen at $\sim 50\%$ efficiency using a thermo-chemical process such as the sulfur-iodine process.



Aim High! Make electricity cheaper than from coal. (Stolen from Robert Hargraves)

100 MW Liquid Fluoride Thorium Reactor Cost Model

Item	\$ Cost	\$ per month, 40 years, 8% financing, levelized	\$ per KWH @ 90%
Construction	200,000,000	1,390,600	0.0214
Start-up U/Pu 100 kg	1,000,000	6,953	0.000108
Thorium fuel	10,700/yr	892	0.00000138
Decomm @ ½ const	100,000,000	960	0.00000148
Operations	1,000,000/yr	83,333	0.00128
TOTAL			0.0228

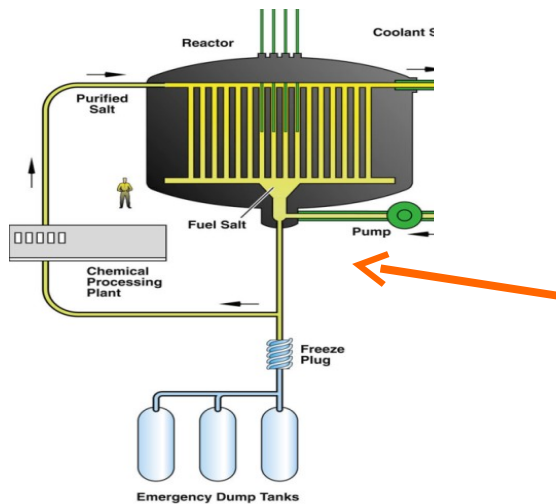
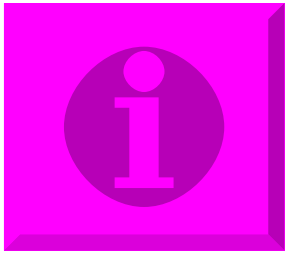
**2008 electric power costs \$/KWH
(delivered)**

**Guangdong 0.0720
Shanghai 0.0790**

References: http://www.nti.org/e_research/cnwm/reducing/heudeal.asp
http://www.bloomberg.com/apps/news?pid=20601080&refer=asia&sid=aV_2FPIVxISE

Aim High! Use automated controls, backed by inherent passive safety.

(*) Stolen from Robert Hargraves
<http://rethinkingnuclearpower.googlepages.com/aimhigh>



- Implement high reliability systems for automated, unattended plant operations.
- Use aeronautical quality computer systems, and technology from unmanned space explorers.
- High temperature expands salt past criticality and ending nuclear reaction.
- In event of a leak or loss of power molten salt flows into containment, cools, solidifies.
Freeze plug.

Operate with no on-site workers.

- Low operational costs.
- No risk of safety over-rides or experimentation.
- No risk of U-233 theft.

Aim High!

(*) Stolen from Robert Hargraves

<http://rethinkingnuclearpower.googlepages.com/aimhigh>

Emulate Boeing mass production.

- Production line.
- One per day.
- Standardized units.
- Computer-aided design, engineering, manufacturing.
- \$200 million per unit.
- Life safety paramount.



Aim High! Check US global warming.

Install one 100 MW LFTR each week to replace US coal power.

(*) Stolen from Robert Hargraves
<http://rethinkingnuclearpower.googlepages.com/aimhigh>

1,600 million
tons CO₂

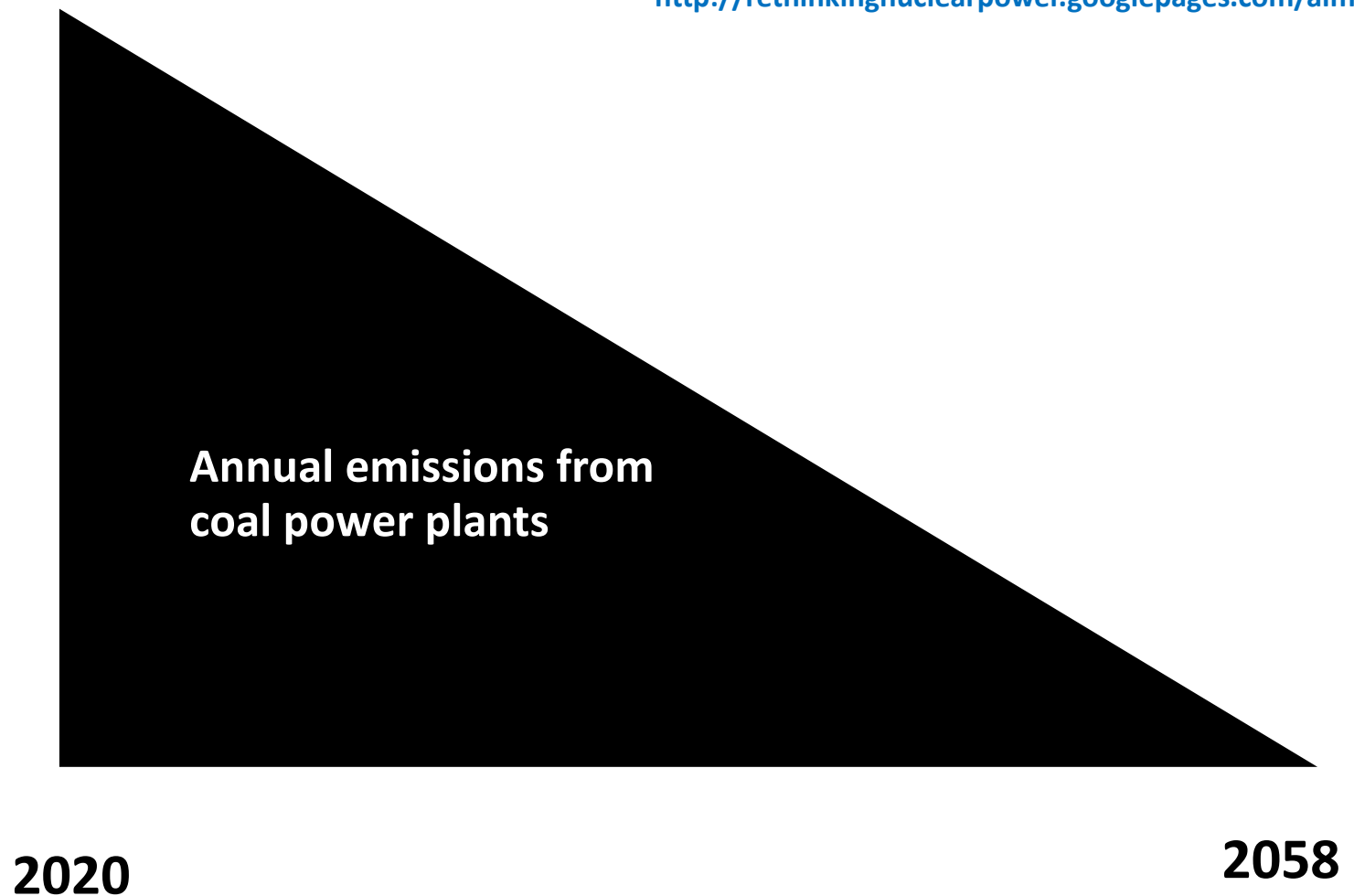


Aim High! Zero emissions worldwide.

Install one 100 MW LFTR each day, worldwide, to replace all coal power.

(*) Stolen from Robert Hargraves
<http://rethinkingnuclearpower.googlepages.com/aimhigh>

10 billion
tons CO₂

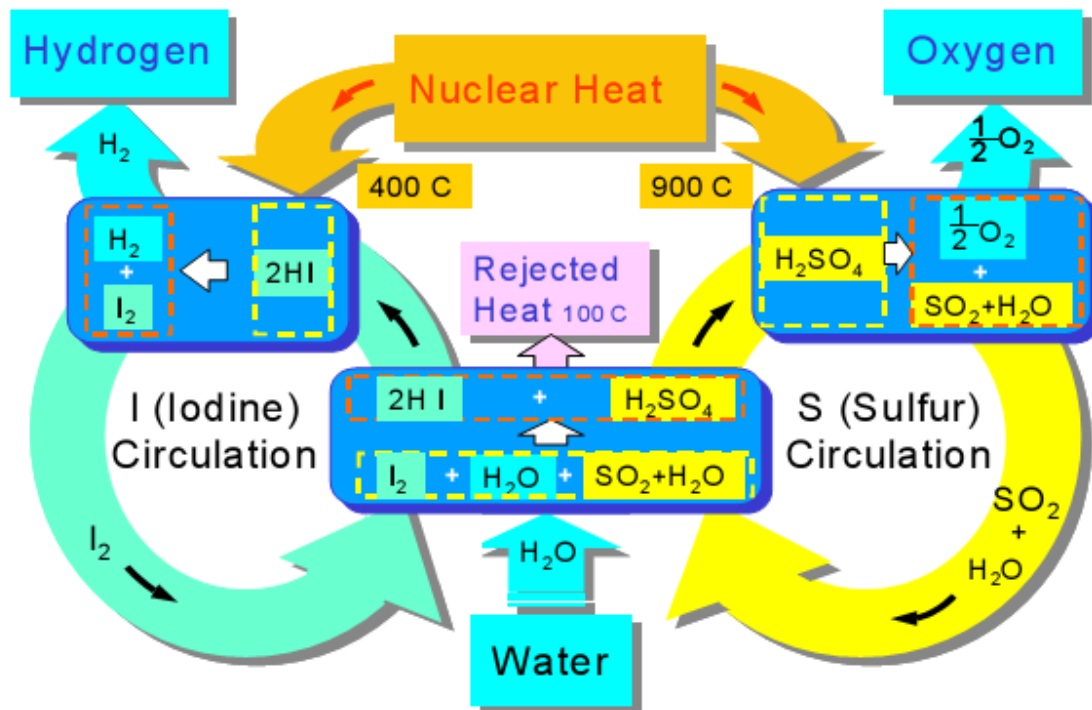


Aim High!

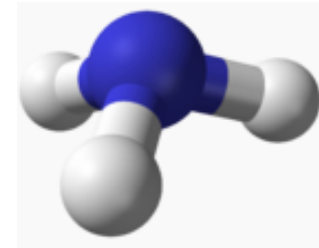
Make motor fuel cheaper than from oil.

(*) Stolen from Robert Hargraves
<http://rethinkingnuclearpower.googlepages.com/aimhigh>

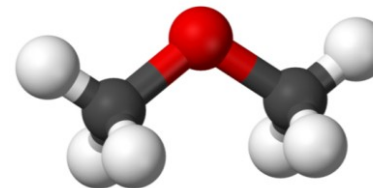
Dissociate water at 900°C to make hydrogen, with sulfur-iodine process.



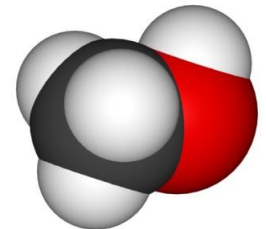
Alternatively start at 700°C with a less efficient process.



Ammonia



Dimethyl ether for diesel

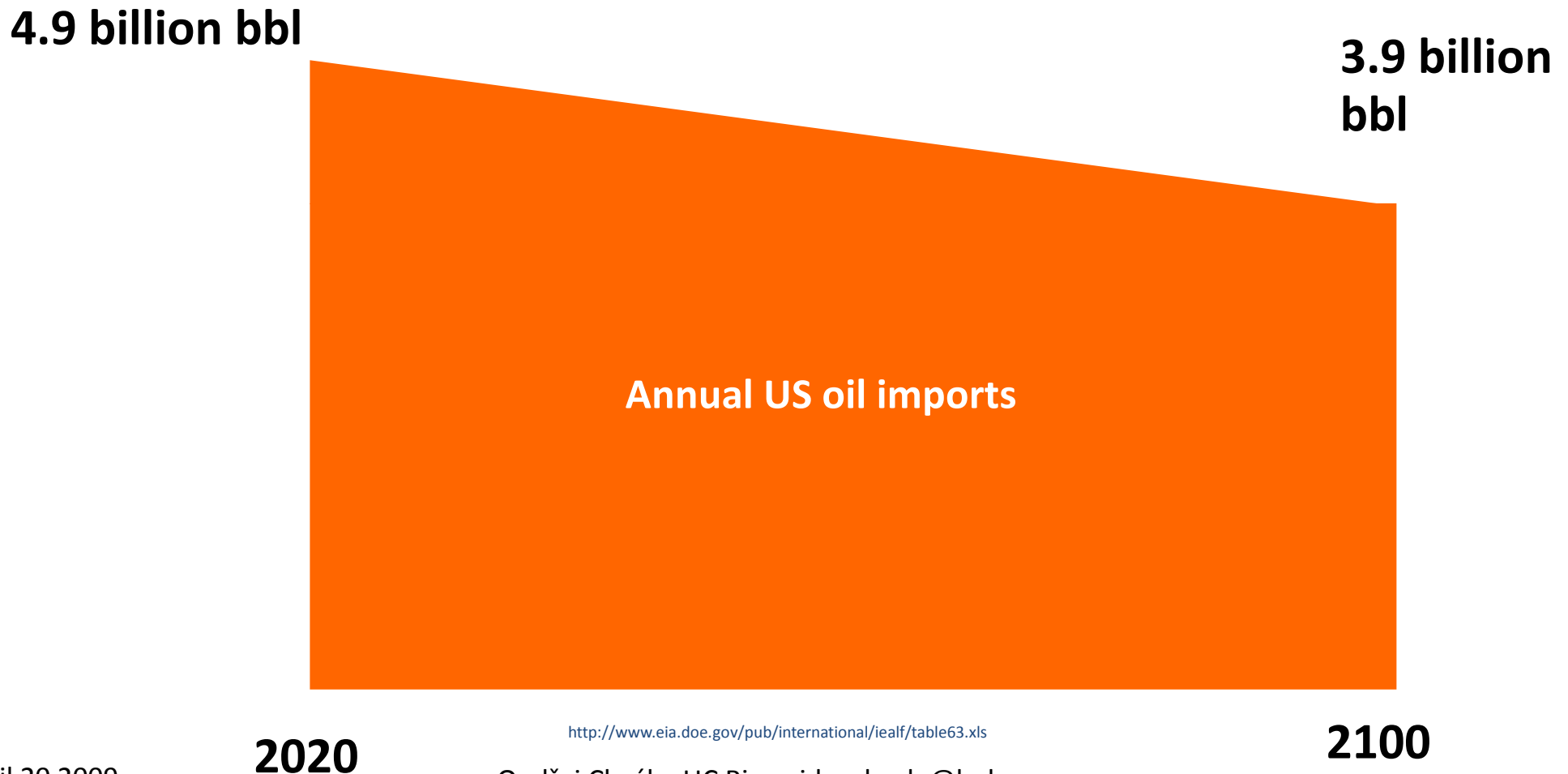


Methanol for gasoline

$\$0.03 / \text{KWH} \times 114,100 \text{ BTU} / \text{gal}$
 $/ 3,419 \text{ BTU} / \text{KWH} / \text{efficiency}$
= \$2.00 per gallon
[if 50% efficient]

Aim High! Cut US oil imports. Hard to do!

Configure for H₂ production (50% eff) and fuel conversion (50%).
100 MW LFTR makes 250,000 bbl/year.
Install one LFTR each week.



<http://www.eia.doe.gov/pub/international/iealf/table63.xls>

Electric cars cut oil imports drastically.



**Chevy Volt recharges with 8 KWH for 40 miles.
100 MW LFTR can power 300,000 cars per day.
Install one LFTR each week.**

4.9 billion bbl



**Best use of petroleum fuel
is for airplanes.**

Ref: <http://www.boeing.com/commercial/gallery/787/index1.html>

Liquid Fluoride Thorium Reactor Conclusions

- ◆ **Thorium is abundant, has incredible energy density, and can be utilized in thermal-spectrum reactors**
 - World thorium energy supplies will last for tens of thousands of years
- ◆ **Solid-fueled reactors have been disadvantaged in using thorium due to their inability to continuously reprocess**
- ◆ **Fluid-fueled reactors, such as the liquid-fluoride reactor, offer the promise of complete consumption of thorium (and DU+TRU waste) in energy generation**
- ◆ **The world would be safer with thorium-fueled reactors**
 - Not an avenue for weapons production
- ◆ **The US should adopt a new “business model” for nuclear power for the country’s long term strategic needs**

Sustainability conclusion

Affordable energy necessary for progress of humanity

Scarcity of **materials** – **recycle** with **plasma arc** technology

Production of energy problematic, due to **large externalities** and **un-sustainability of fossil fuels**

Solar renewables, energy storage – invest into R&D (nanotechnology) instead of subsidizing production & deployment of current expensive and combustion-dependent technology

Contemporary nuclear energy → demonstratively **the best energy** resource we have now

However: **problems** with **scalability** (material requirements due to highly pressurized water → cost, long term viability of uranium sources, inefficient mineral resource use → waste)

Fast spectrum breeders are mature technology which solves many of these issues

Molten salt reactors are demonstrated technology which can solve all these issues

"Public opinion [is the] lord of the universe.",

"When public opinion changes, it is with the rapidity of thought."

[Thomas Jefferson on Politics & Government]

<http://etext.virginia.edu/jefferson/quotations/jeff0300.htm>

Thank you for your attention. Questions?

Backup slides

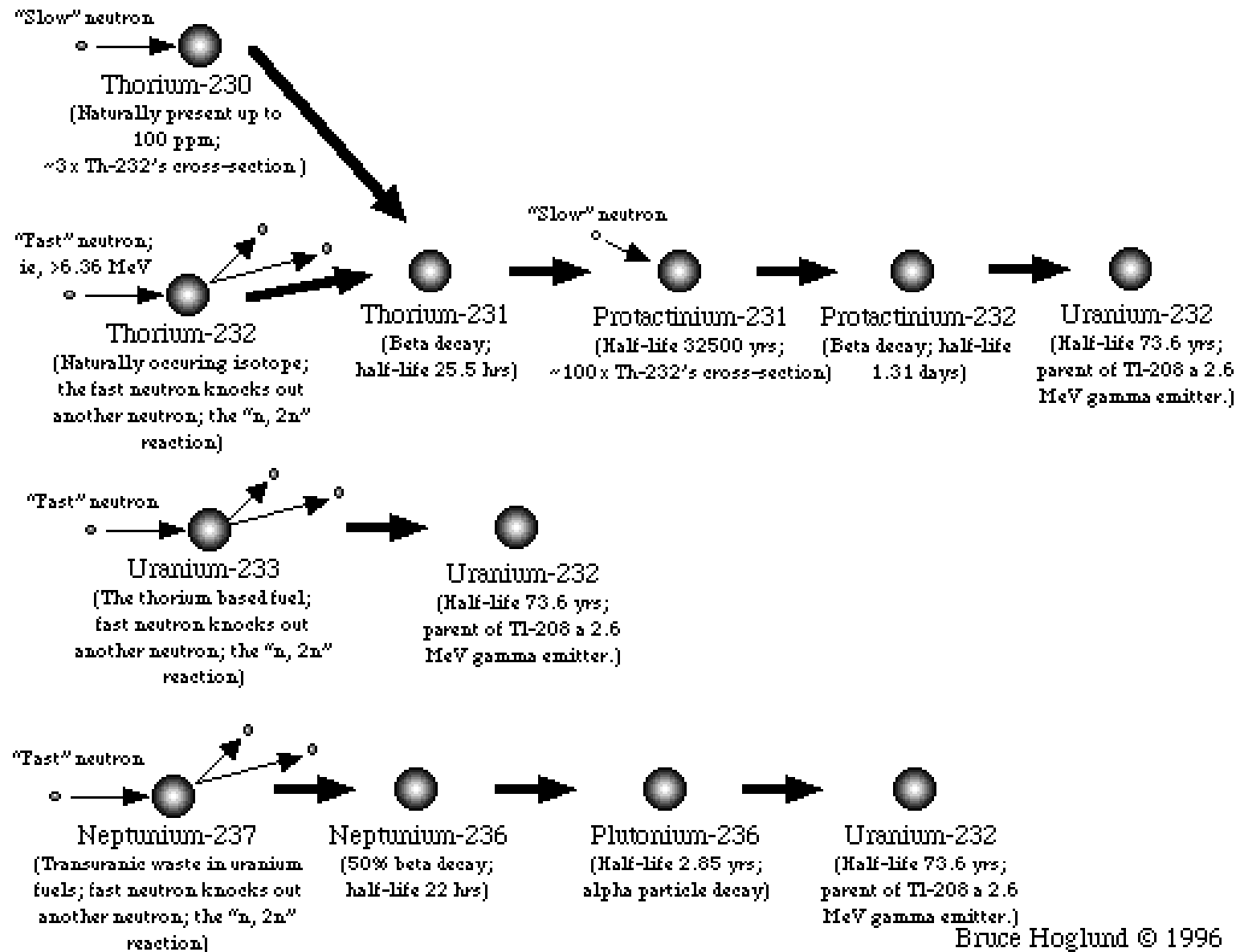
Single or two fluids?

Single fluid – fuel salt contains fertile material
breeding impossible (without problematic Pa removal)
converter OK

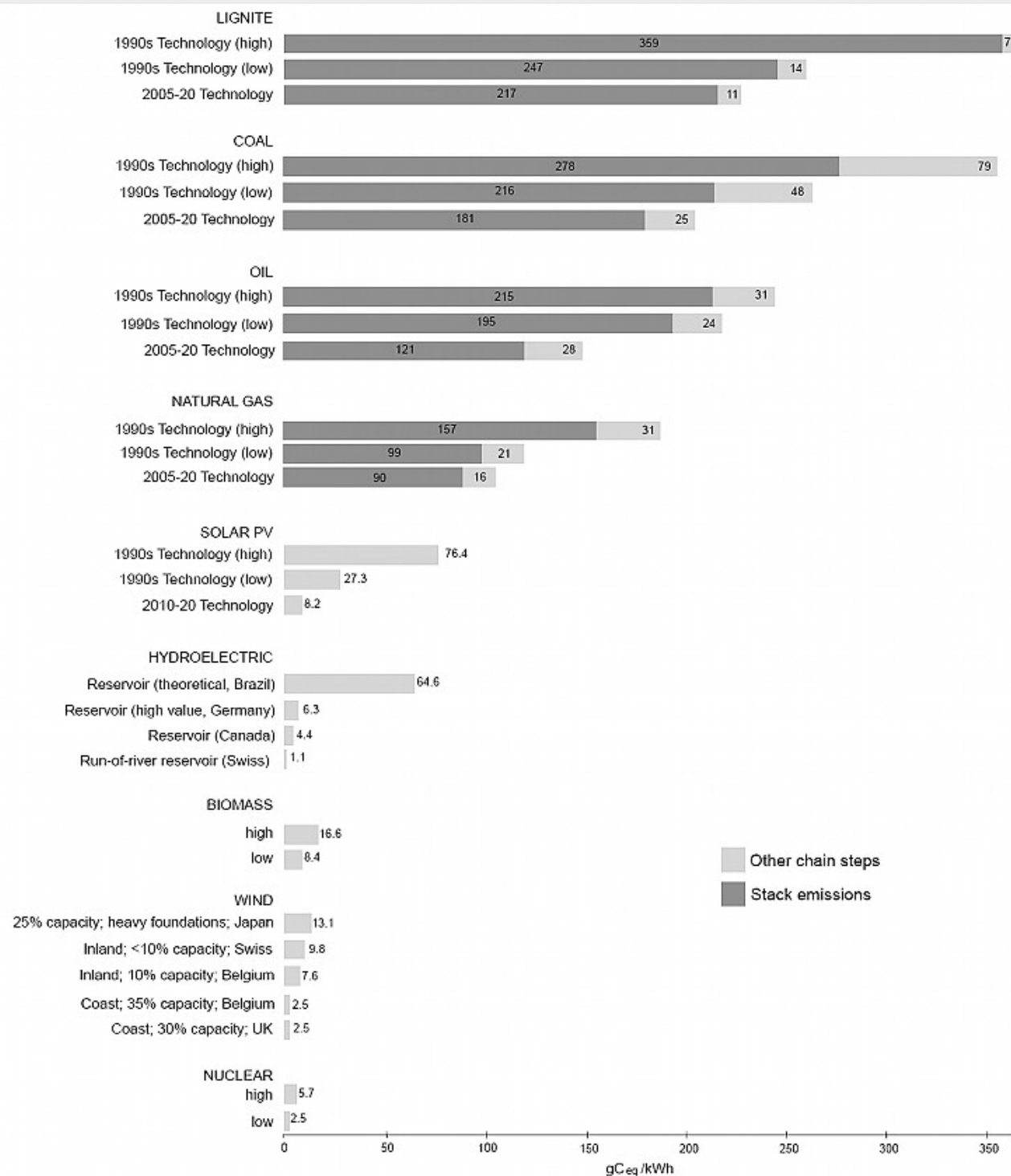
Two fluid – separate fuel and blanket (Th) salts
breeding OK
simple reprocessing
technically, a highly enriched uranium

Denatured (adding U238 to make fuel “LEU”) operation possible

ORNL-TM-7207: Denatured MSR with Once-Through Fueling
<http://www.energyfromthorium.com/forum/viewtopic.php?f=8&t=268>



RANGE OF TOTAL GREENHOUSE GAS EMISSIONS FROM ELECTRICITY PRODUCTION CHAINS



Source: IAEA

Middle east & nuclear

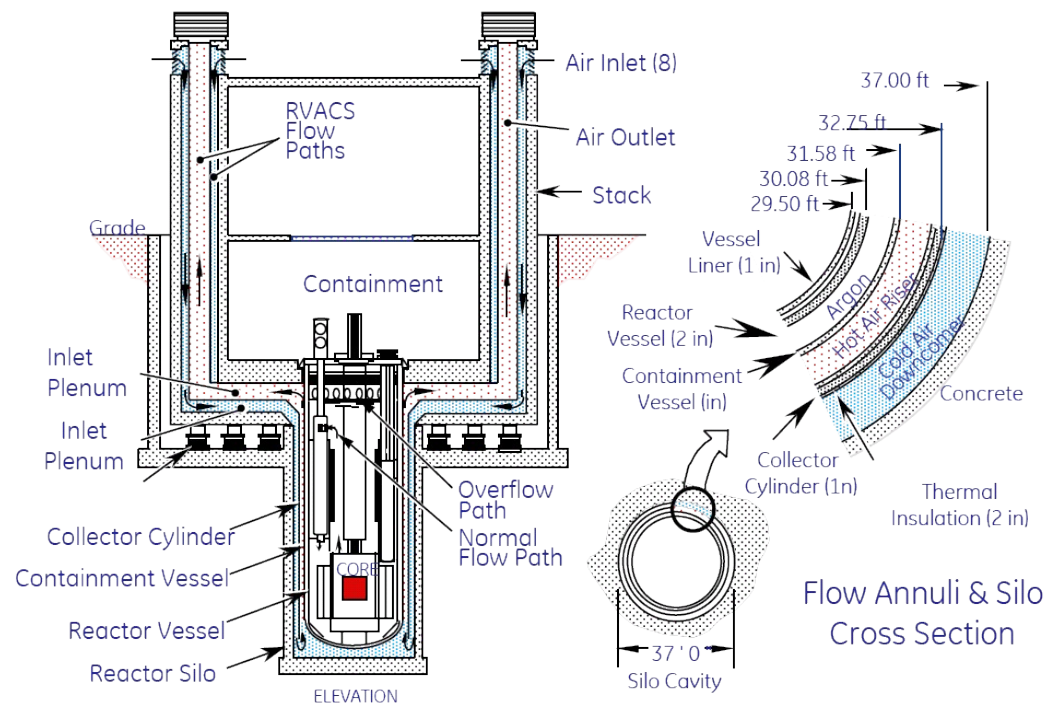
<http://www.energyfromthorium.com/forum/viewtopic.php?f=39&t=1419>

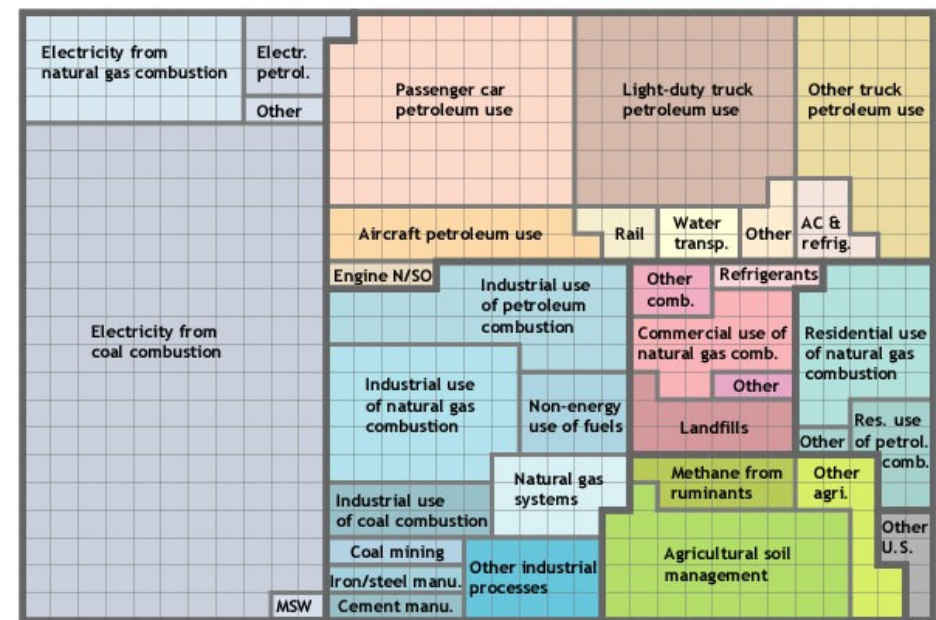
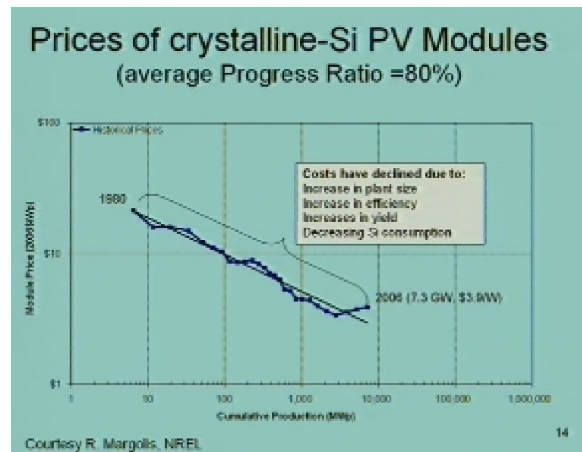
Below are the nuclear aspirations of countries across the Middle East.

- Algeria aims to build its first commercial nuclear power station by around 2020 and to build another every five years after that, energy minister Chakib Khelil said in February.
- He said Algeria had atomic energy agreements with Argentina, China, France and the United States and was also in talks with Russia and South Africa.
- The OPEC member has plentiful oil and gas reserves but wants to develop other energy sources to free up more hydrocarbons for export. Algeria has big uranium deposits and two nuclear research reactors but no uranium enrichment capacity. Algeria and China agreed a year ago to cooperate on developing civilian nuclear power.
- EGYPT: -- Egypt said in Oct. 2007 it would build several civilian nuclear power stations to meet its growing energy needs.
- In December 2008 Egypt chose Bechtel Power Corp as contractor to design and consult on the country's first nuclear power plant. Bechtel offered to do the work for around 1 billion Egyptian pounds (\$180 million) over a 10-year period, it said.
- Bechtel will consider five locations for the first nuclear plant, starting with Dabaa on the Mediterranean coast west of Alexandria.
- IRAN: -- Iranian President Mahmoud Ahmadinejad inaugurated its first nuclear fuel production plant on Thursday. He said the plant would produce fuel for Iran's Arak heavy water reactor.
- Iran plans to start up its first atomic power plant in mid-2009, its foreign minister said in March. Tehran says the 915-megawatt Russian-built Bushehr plant will be used only for generating electricity in the world's fourth largest oil producer. But the West accuses Iran of covertly seeking to make nuclear weapons.
- JORDAN: -- Jordan had talks with French nuclear energy producer Areva in 2008 to construct a nuclear power reactor, Jordanian officials said.
- They said Areva was a frontrunner among several international firms in talks with the kingdom to develop a nuclear reactor to meet rising demand for power.
- Jordan has signed agreements with France, China and Canada to co-operate on the development of civilian nuclear power and the transfer of technology.
- KUWAIT: -- Kuwait is considering developing nuclear power to meet demand for electricity and water desalination, the country's ruler said in February 2009.
- "A French firm is studying the issue," daily al-Watan quoted Emir Sheikh Sabah al-Ahmad al-Sabah as saying.
- Nuclear power would save fuel that could be exported but which is currently used to generate electricity and operate water desalination plants, he said.
- LIBYA: -- Moscow and Libya said in Nov. 2008 they were negotiating a deal for Russia to build nuclear research reactors for the North African state and supply fuel.
- Officials said a document on civilian nuclear cooperation was under discussion at talks between Libyan leader Muammar Gaddafi and Russian Prime Minister Vladimir Putin.
- Under the deal, Russia would help Libya design, develop and operate civilian nuclear research reactors and provide fuel for them.
- QATAR: -- Initial Qatari interest in nuclear power plants has waned with the fall in international oil and gas prices, a Qatari official said in Nov. 2008.
- If Qatar decided to go ahead with building a nuclear plant, feasibility studies showed it would be unlikely to bring a reactor into operation before 2018.
- French power giant EDF signed a memorandum with Qatar in early 2008 for cooperation on development of a peaceful civilian nuclear power programme.
- UAE: -- The Bush administration signed a nuclear deal with the United Arab Emirates in January, despite concerns in Congress that the UAE was not doing enough to curb Iran's atomic plans. Obama has advanced this policy wholeheartedly primarily because UAE absolutely insists on it.

GE-Hitachi PRISM

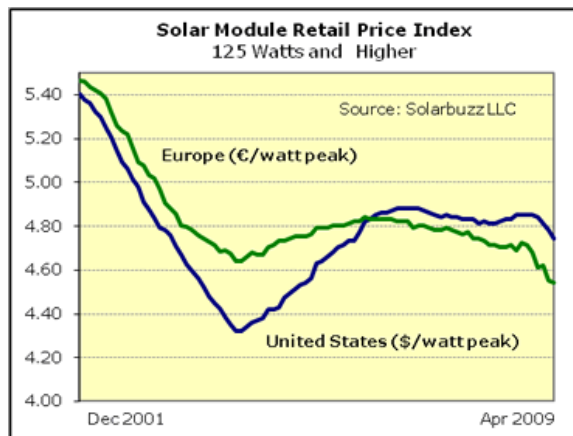
PRISM Reactor Vessel Auxiliary Cooling System



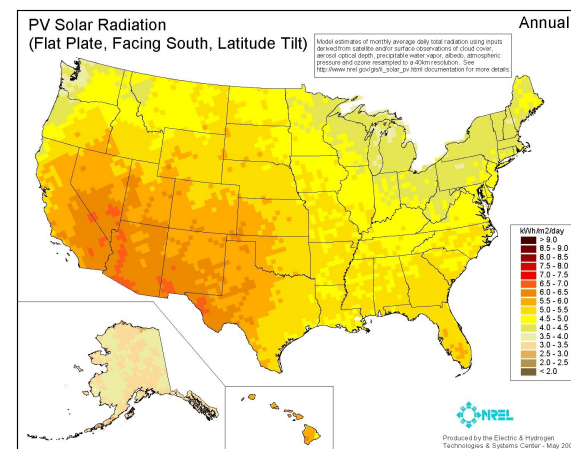


© Jeffrey Winters

http://coal2nuclear.com/gas_to_electricity.htm



from: <http://www.solarbuzz.com/Moduleprices.htm>



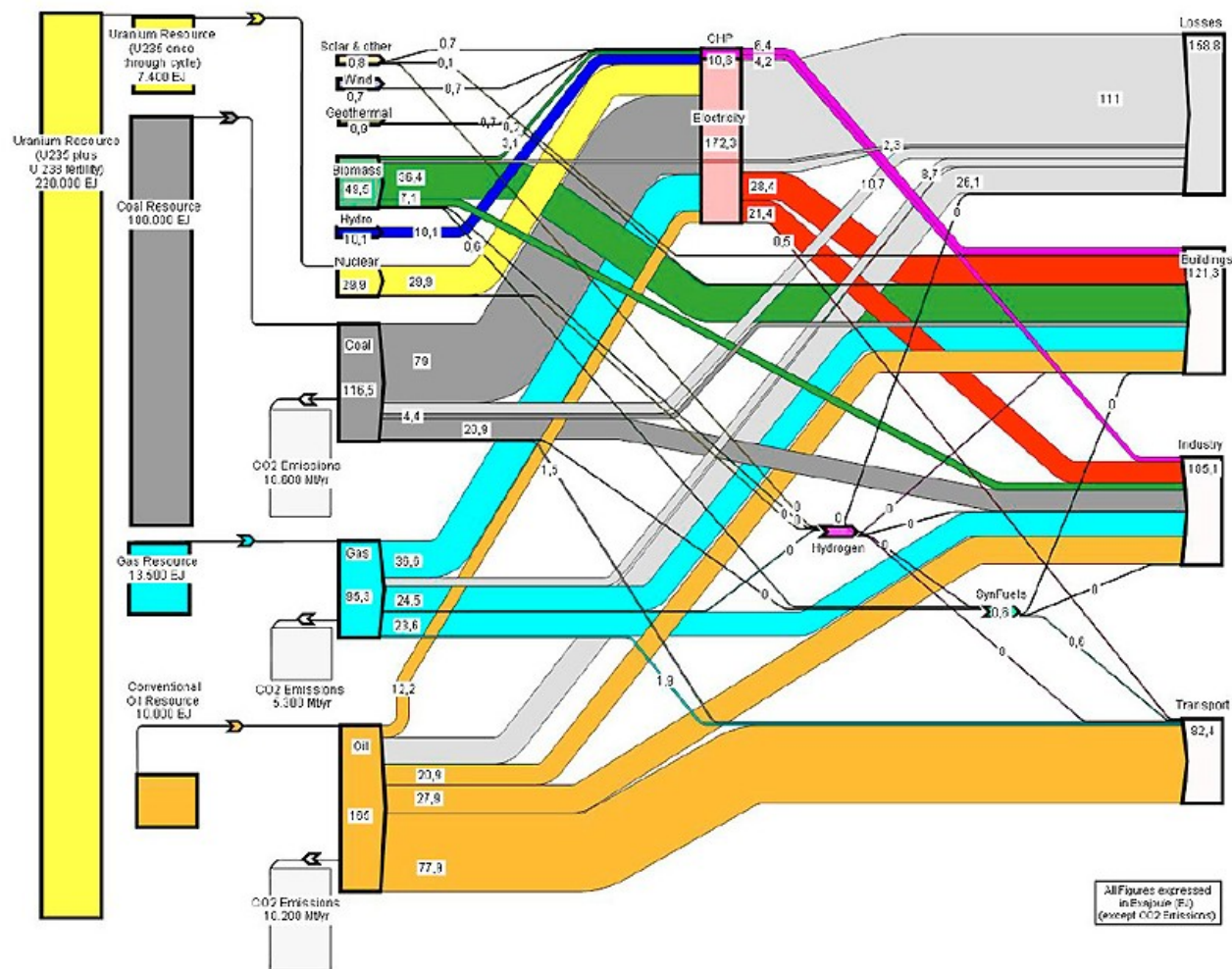


Figure 4.4: Global energy flows (EJ in 2004) from primary energy through carriers to end-uses and losses. Related carbon dioxide emissions from coal, gas and oil combustion are also shown, as well as resources (vertical bars to the left).

Energy Production Subsidies

Federal Financial Interventions and Subsidies in Energy Markets 2007

Table 35. Subsidies and Support to Electricity Production: Alternative Measures

Fuel/End Use	FY 2007 Net Generation (billion kilowatthours)	Alternative Measures of Subsidy and Support	
		Subsidy and Support Value 2007 (million dollars)	Subsidy and Support Per unit of Production (dollars/megawatthours)
Coal	1,946	854	0.44
Refined Coal	72	2,156	29.81
Natural Gas and Petroleum Liquids	919	227	0.25
Nuclear	794	1,267	1.59
Biomass (and Biofuels)	40	36	0.89
Geothermal	15	14	0.92
Hydroelectric	258	174	0.67
Solar ¹	1	14	24.34
Wind	31	724	23.37
Landfill Gas	6	8	1.37
Municipal Solid Waste	9	1	0.13
Unallocated Renewables	NM	37	NM
Renewables (subtotal)	360	1,008	2.80
Transmission and Distribution	NM	1,235	NM
Total	4,091	6,747	1.65

NOTES: Total may not equal sum of components due to independent rounding.

Unallocated renewables include projects funded under Clean Renewable Energy Bonds and the Renewable Energy Production Incentive.

NM = Not meaningful.

¹Net generation rounded to the nearest whole number. The actual value is 583 million kilowatthours.

Sources: Energy Information Administration, Forms EIA-906, "Power Plant Report;" Form EIA-920, "Combined Heat and Power Plant Report;" October 2006-September 2007.

Besides: wind, solar – thousands of years spent on R&D

From page 105 of the report <http://www.eia.doe.gov/oiaf/servicerpt/subsidy2/index.html>

Are Fluoride Salts Corrosive?

- ♦ Fluoride salts are fluxing agents that rapidly dissolve protective layers of oxides and other materials.
- ♦ To avoid corrosion, molten salt coolants must be chosen that are thermodynamically stable relative to the materials of construction of the reactor; that is, the materials of construction are chemically noble relative to the salts.
- ♦ This limits the choice to highly thermodynamically-stable salts.
- ♦ This table shows the primary candidate fluorides suitable for a molten salt and their thermo-dynamic free energies of formation.
- ♦ The general rule to ensure that the materials of construction are compatible (noble) with respect to the salt is that the difference in the Gibbs free energy of formation between the salt and the container material should be >20 kcal/(mole °C).

Table 2. Properties of Fluorides for Use in High-Temperature Reactors

Compound	Free Energy of Formation at 1000°K (kcal/F atom)	Melting Point (°C)	Absorption Cross Section ^a for Thermal Neutrons (barns)
Structural metal fluorides			
CrF ₂	-74	1100	3.1
FeF ₂	-66.5	930	2.5
NiF ₂	-58	1330	4.6
Diluent fluorides			
CaF ₂	-125	1330	0.43
LiF	-125	870	0.033 ^b
BaF ₂	-124	1280	1.17
SrF ₂	-123	1400	1.16
CeF ₃	-118	1324	0.7
YF ₃	-113	1144	1.27
MgF ₂	-113	1270	0.063
RbF	-112	790	0.70
NaF	-112	1000	0.53
KF	-109	880	1.97
BeF ₂	-104	545	0.010
ZrF ₄	-94	912	0.180
AlF ₃	-90	1040	0.23
ZnF ₂	-71	872	1.06
SnF ₂	-62	213	0.6
PbF ₂	-62	850	0.17
BiF ₃	-50	727	0.032
Active fluorides			
ThF ₄	-101	1115	
UF ₄	-95.3	1035	
UF ₃	-100.4	1495	

^aOf metallic ion.

^bCross section for ⁷Li.

Thorium, uranium, and all the other heavy elements were formed in the final moments of a supernova explosion billions of years ago.

Our solar system: the Sun, planets, Earth, Moon, and asteroids formed from the remnants of this material.