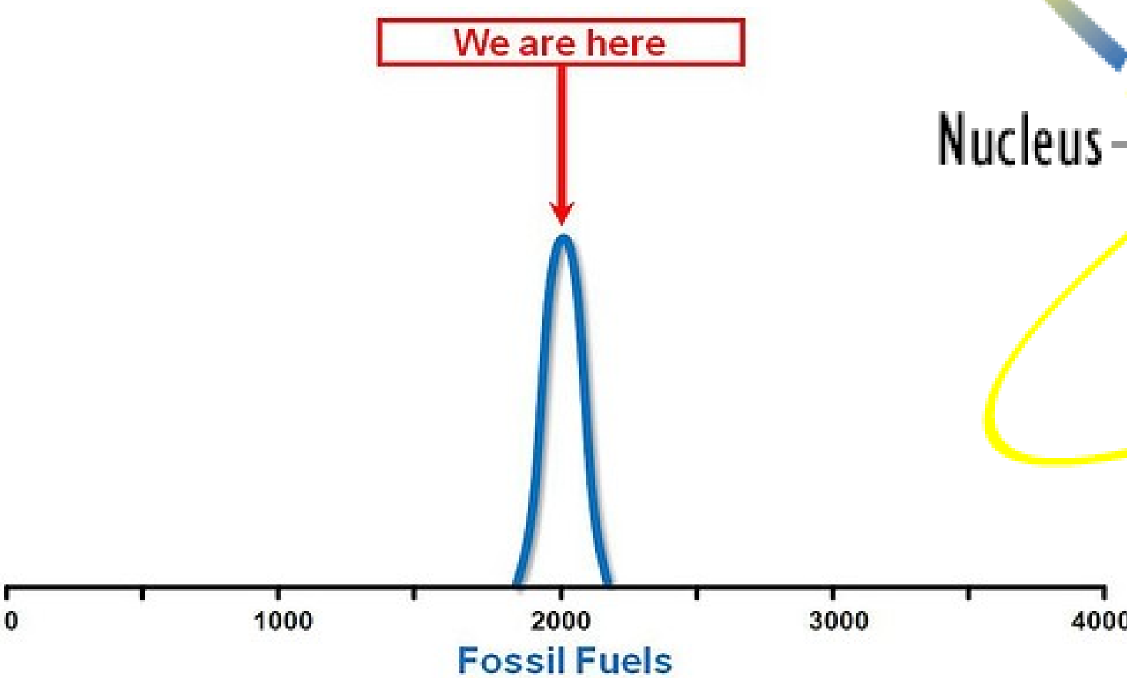
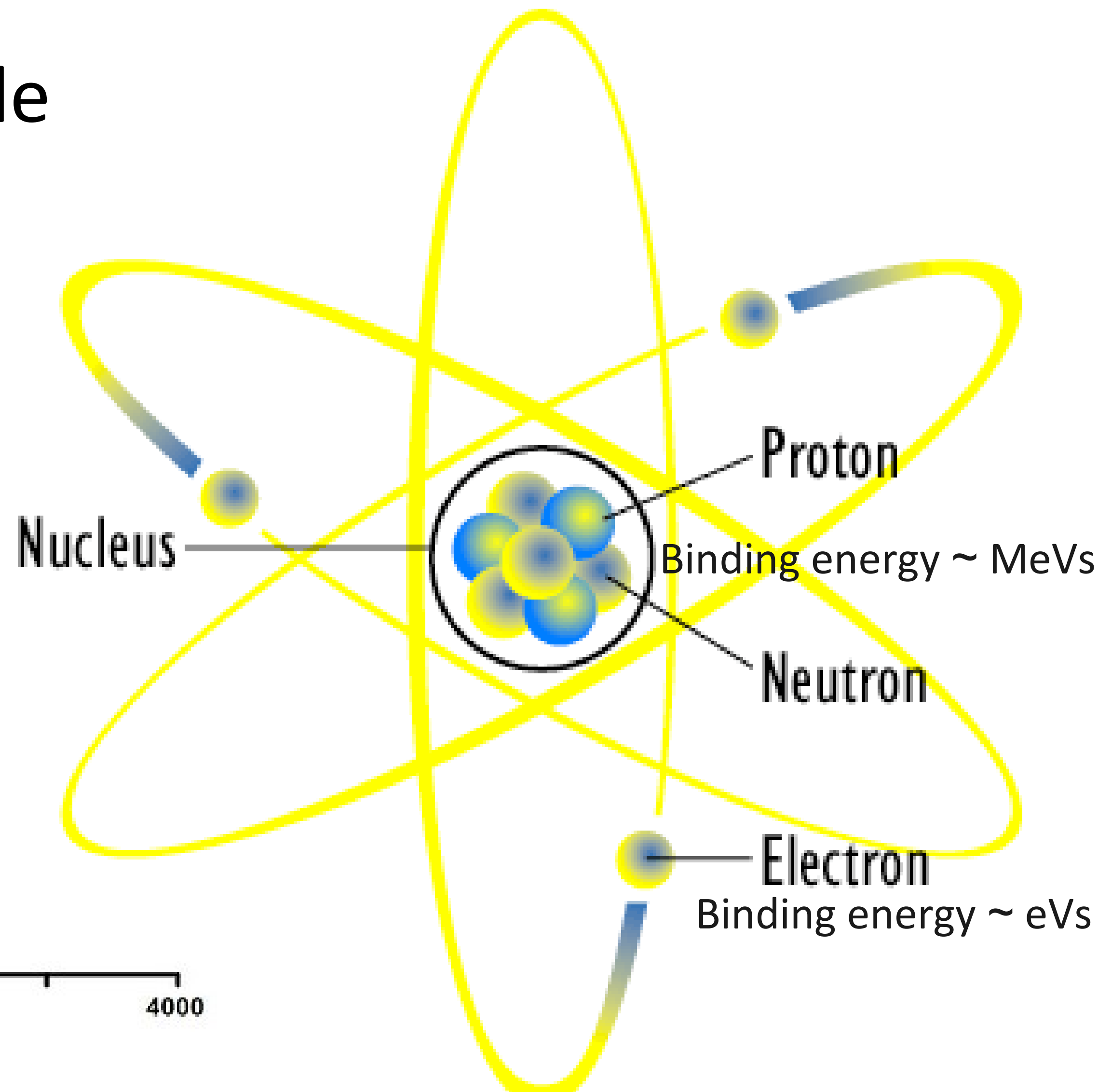
The future of nuclear fission energy:

a replacement for our unsustainable and environmental destructive use of limited fossil fuels?

Ondřej Chvála, UC Riverside
ondrejch@gmail.com

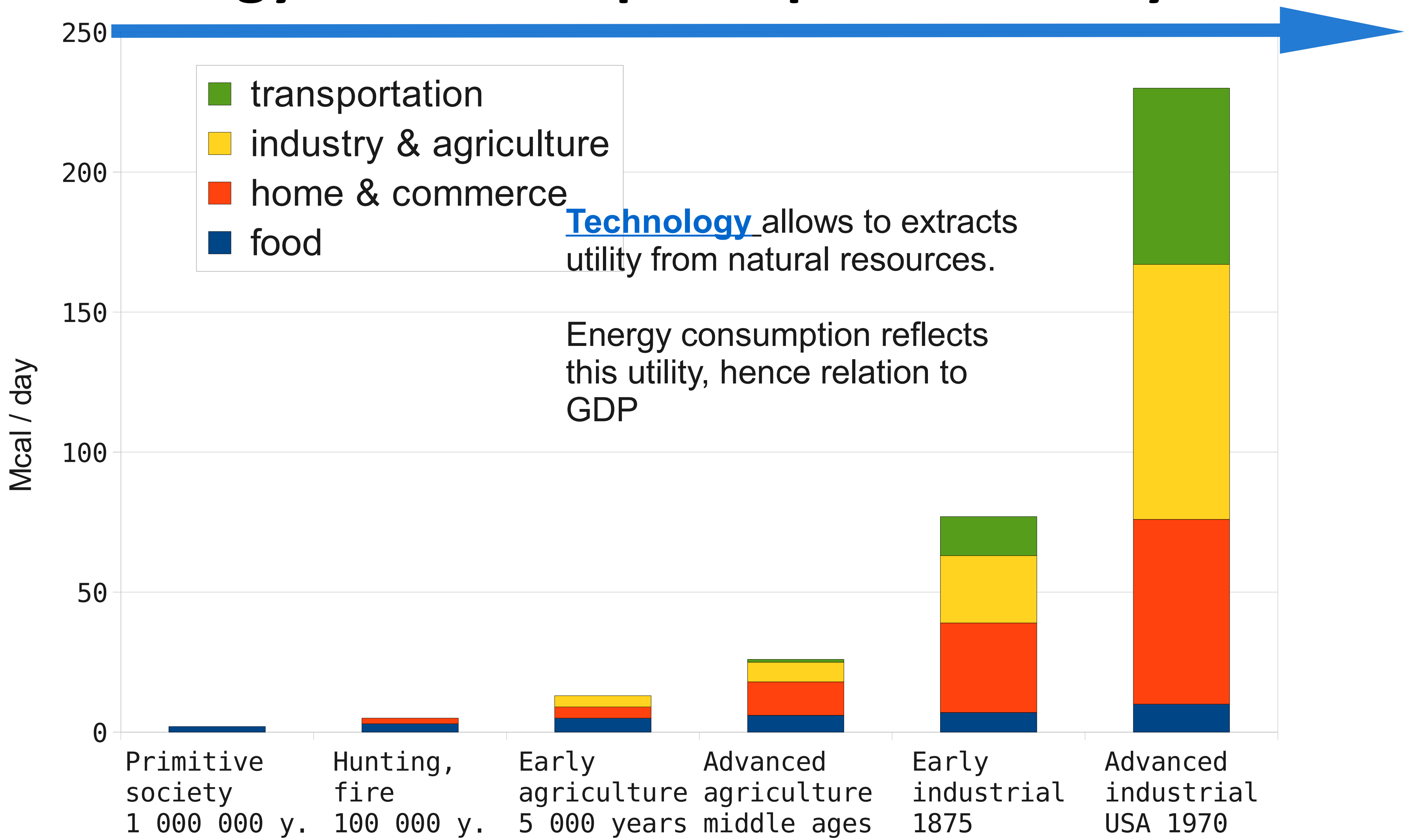




Outline

- Energy consumption in history and likely future
- Perils of fossil fuels
- Limits of "submarine reactors" (LWRs)
- Why thorium and molten salt systems
  - Historic interlude
  - Relevant physics considerations
  - Present situation and future prospects
- Slides are for discussion and future reference, most will be skipped in the talk :-)

Energy extraction per capita in history



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

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.

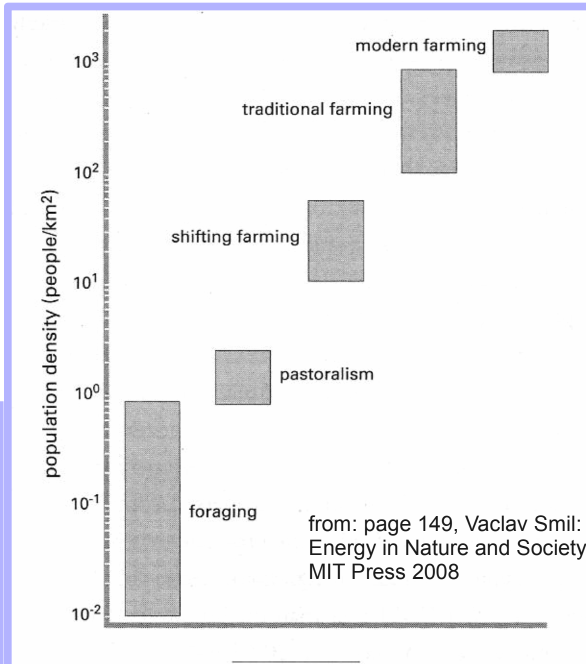
500 energy slaves/capita which heat homes, water, transport people and stuff, drive machines in factories etc.

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

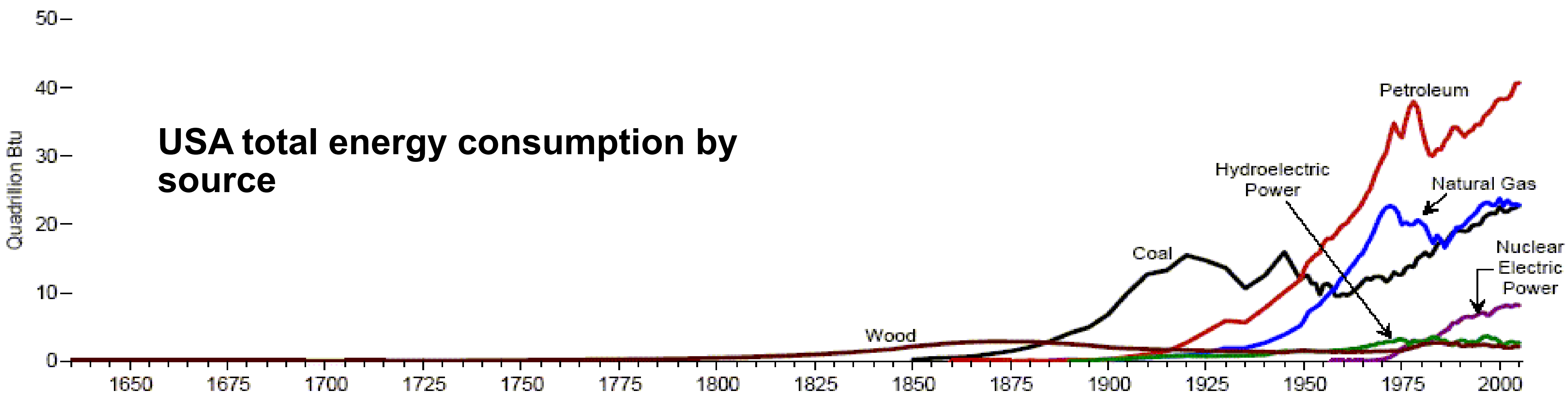
"Carrying capacity" for humans depends on civilization stage and resp. technology (now from Haber-Bosch to satellite controlled farming)



6.1 Ranges of population densities supportable by intensifying modes of food provision.

USA – historic perspective of energy use

USA total energy consumption by source

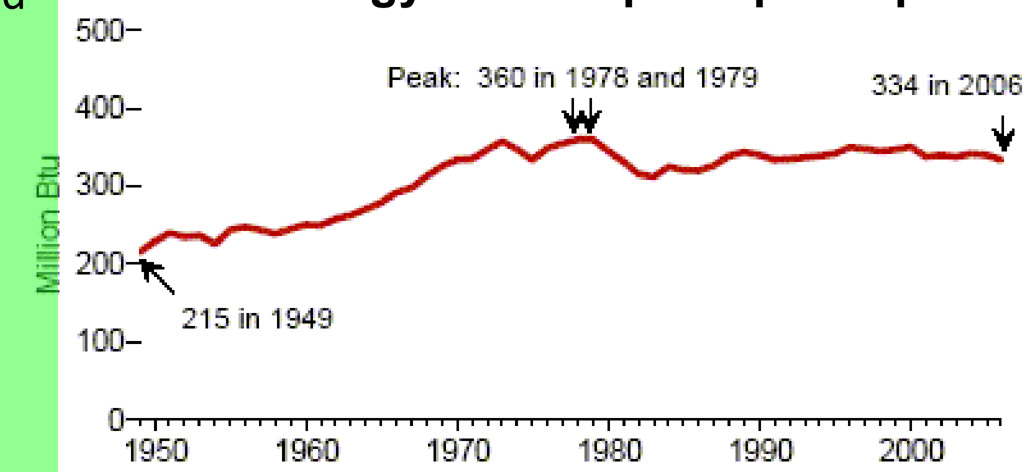


(*) plots from:
http://www.eia.doe.gov/emeu/aer/ep/ep_frame.html

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.

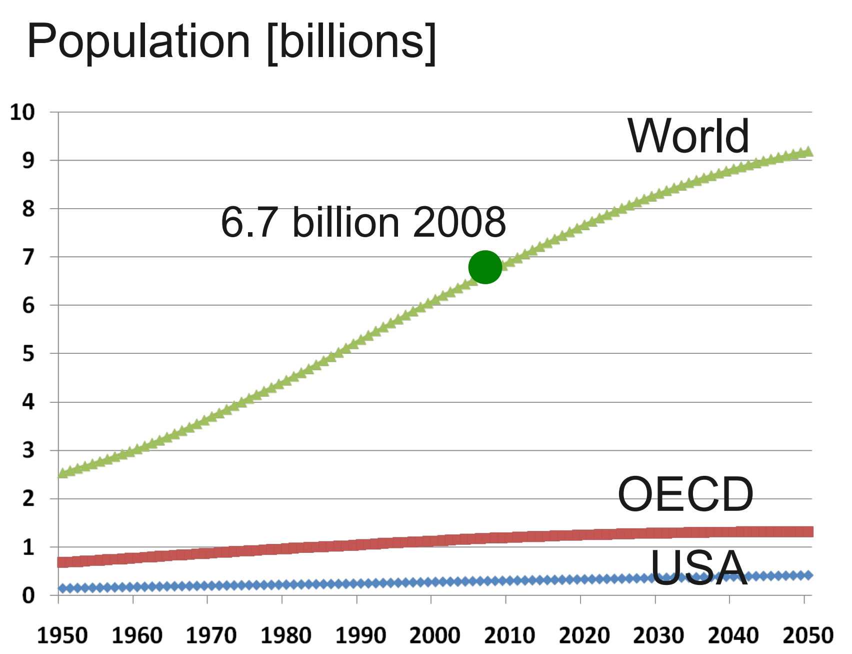
Total energy consumption by humans will rise as billions living in 3rd world countries transit from agriculture and industrial civilizations to the technological age.

USA energy consumption per capita



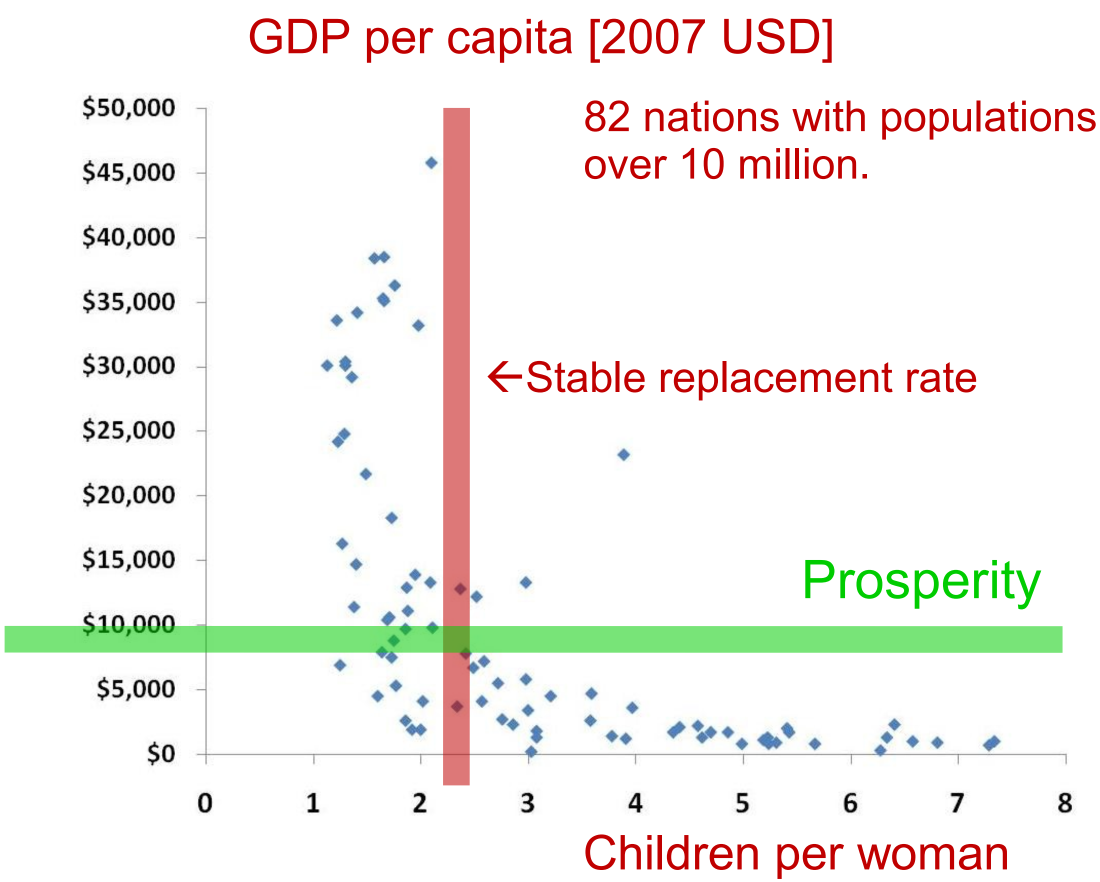
Population

Population is stable in developed countries



References:
http://caliban.sourceoecd.org/vl=1260748/cl=17/nw=1/rpsv/factbook/010101.htm
http://www.oecd.org/dataoecd/13/38/16587241.pdf

Prosperity stabilizes population

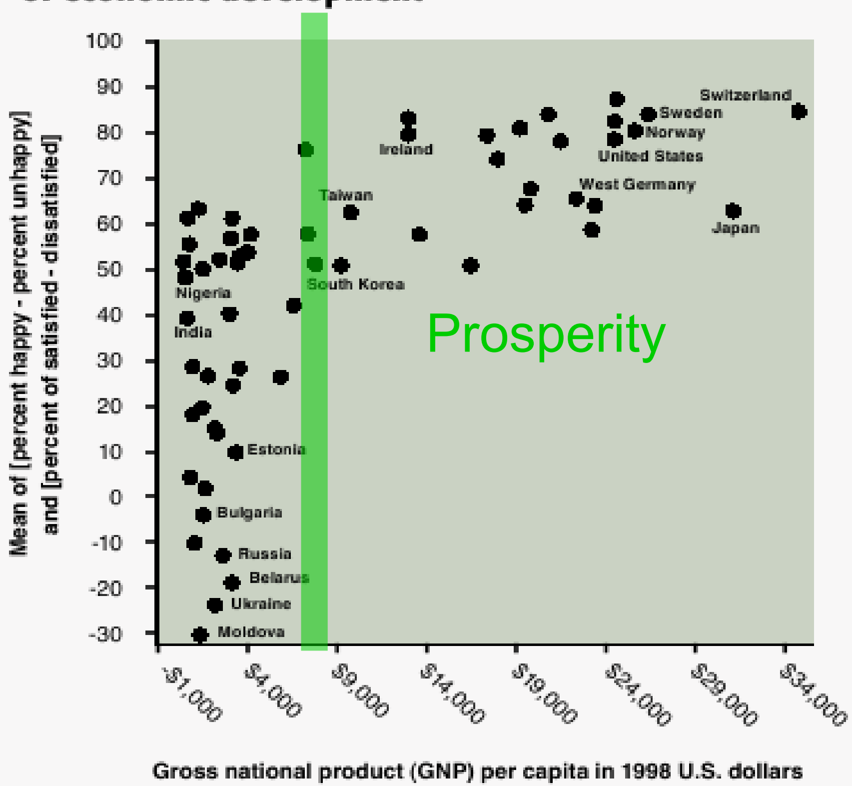


https://www.cia.gov/library/publications/the-world-factbook/docs/rankorderguide.html

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

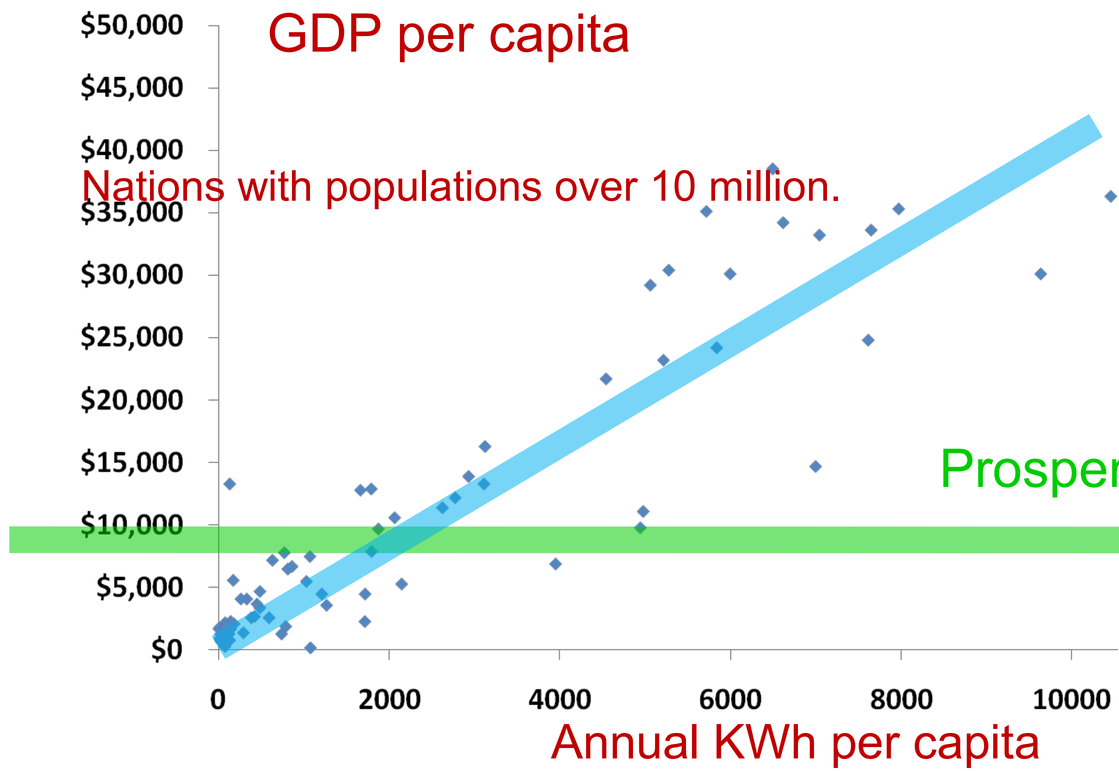
Quality of life and energy consumption I

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



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).

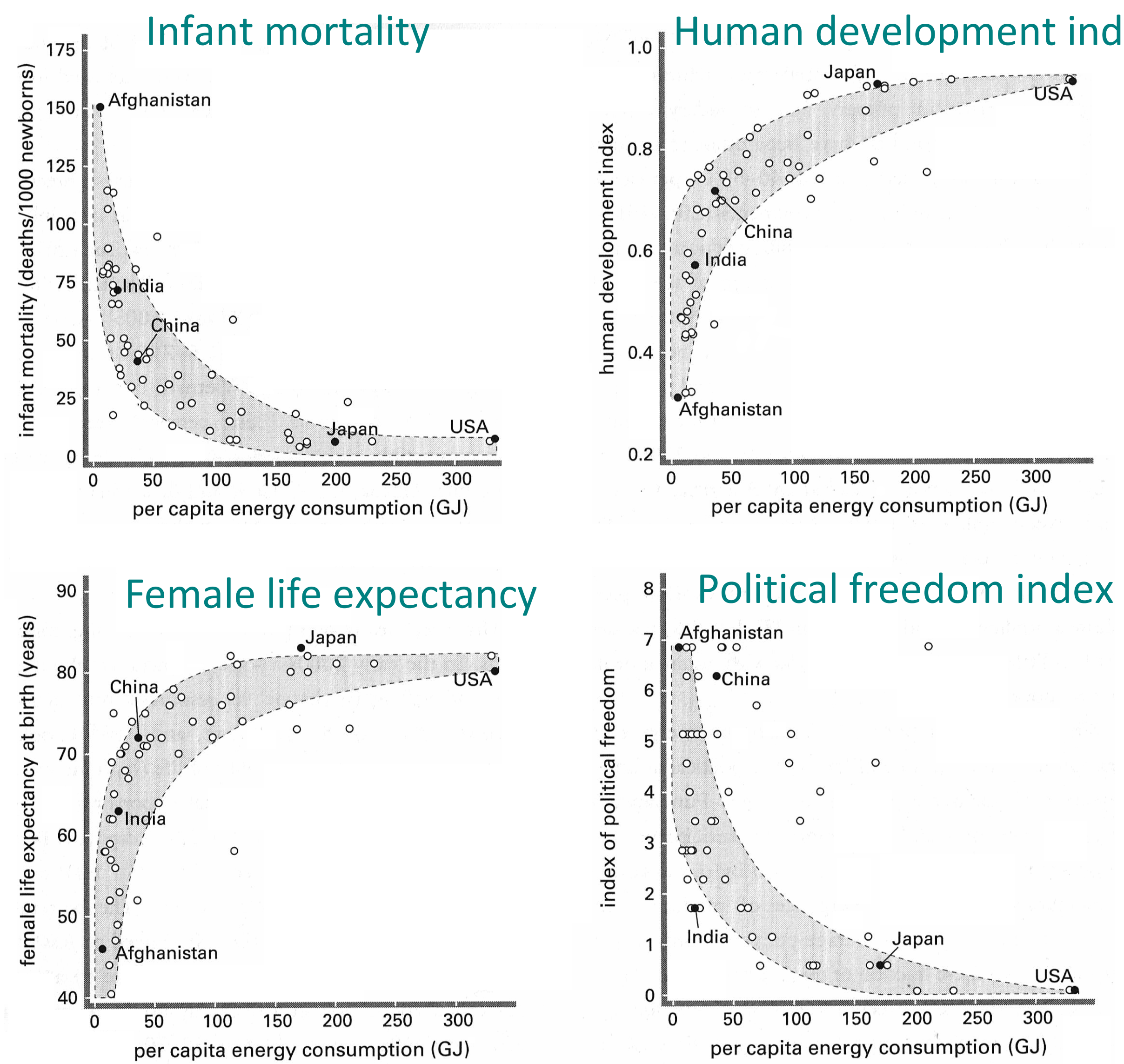


References:
http://rethinkingnuclearpower.googlepages.com/aimhigh
https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html

$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



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

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

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

Ondřej Chvála, chvala@bnl.gov

Conservation and efficiency

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.

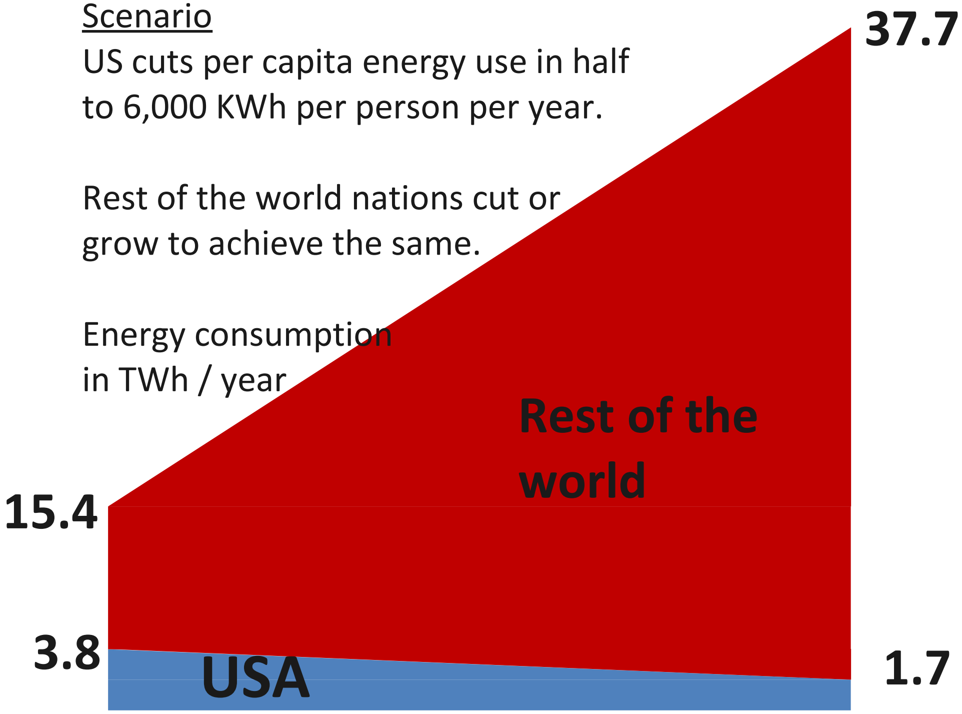
Conservation through increasing energy efficiency is inefficient, even futile.

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

<u>Scenario</u>
US cuts per capita energy use in half to 6,000 KWh per person per year.

Rest of the world nations cut or grow to achieve the same.

Energy consumption in TWh / year

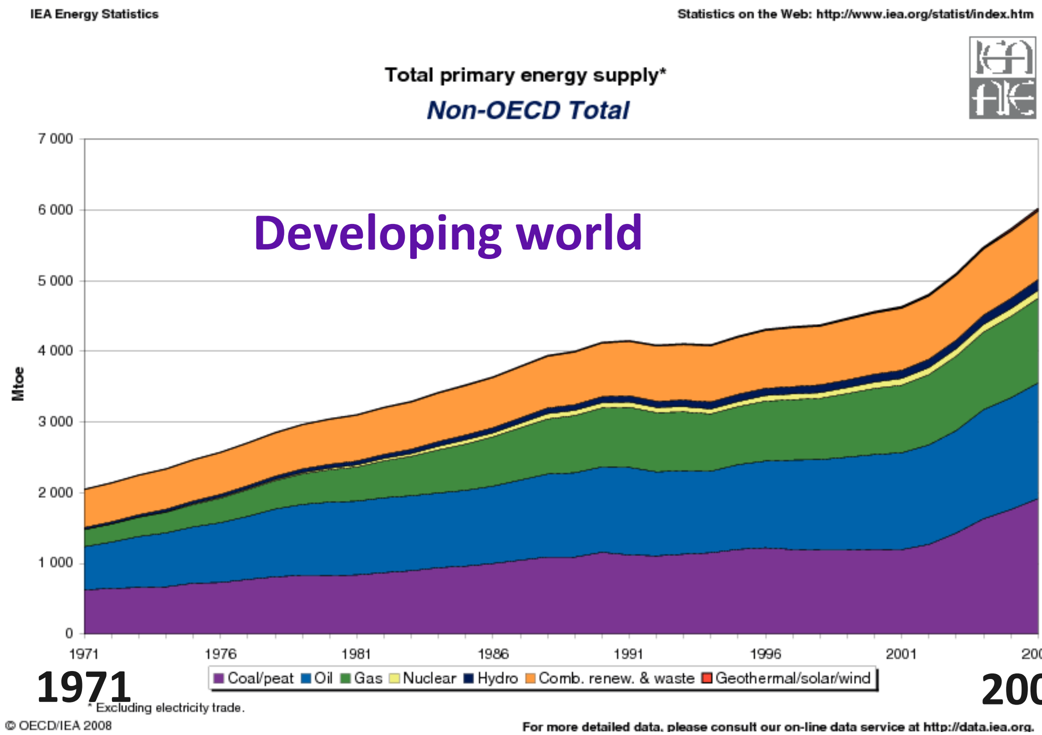


<u>Jevons paradox</u> <u>(1865)</u>: increase in efficiency of utilizing a resource increases used quantity of the resource due to a) more work is **substituted** by using of the resource; b) cheaper products increased **disposable income** thus buying more.

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 benefitial).

Problems with energy production ...



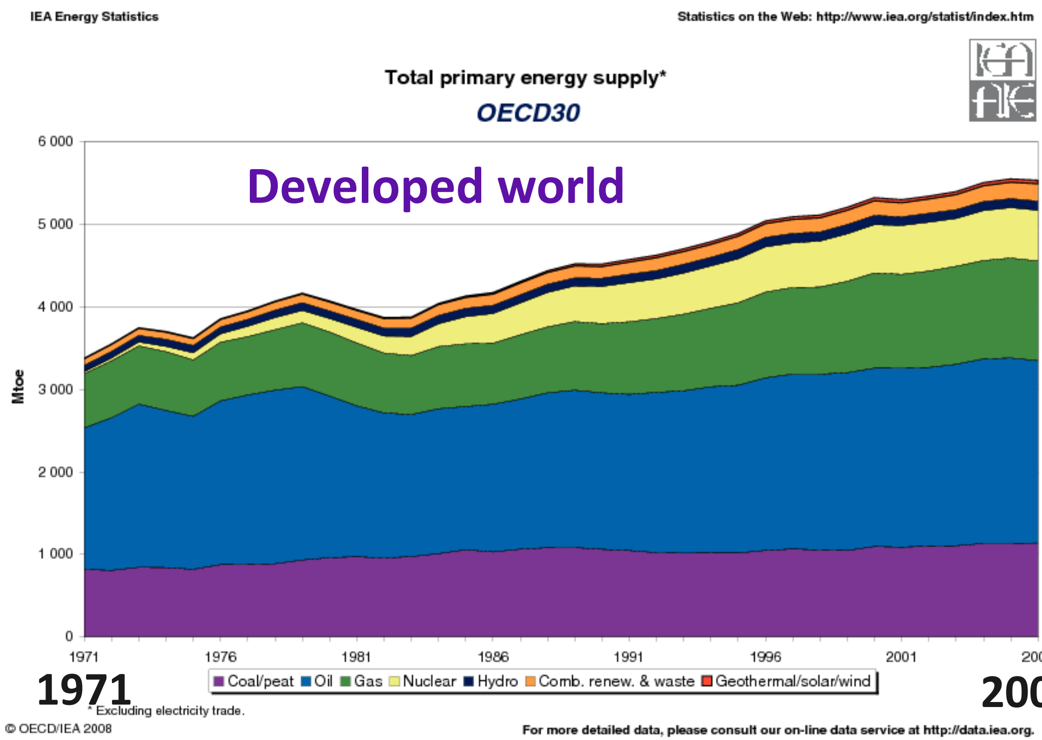
1971 2006

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

Hydro

Fossil fuels

Wind+
Solar+
Geothermal+
Tidal+...



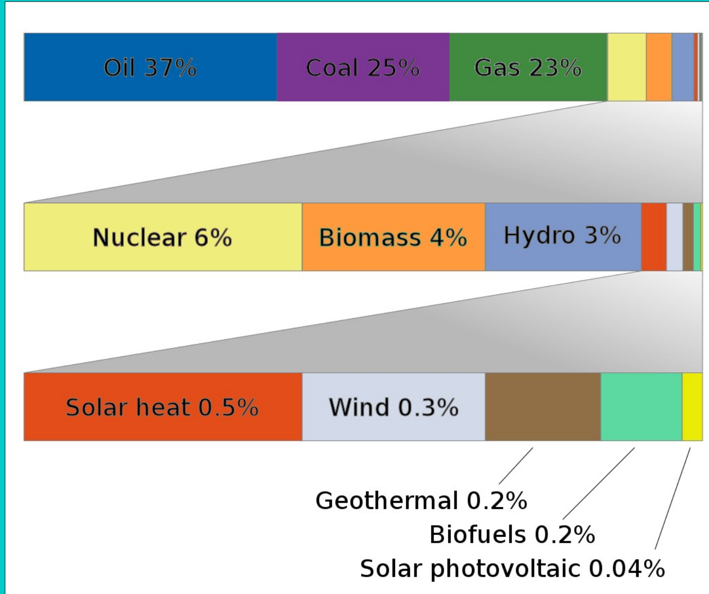
1971 2006

Nuclear

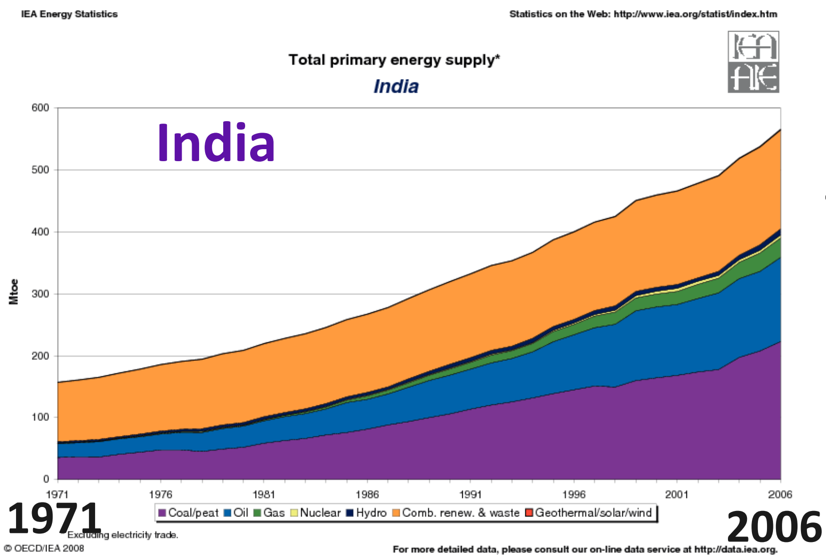
Fossil fuels

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

World energy usage by source

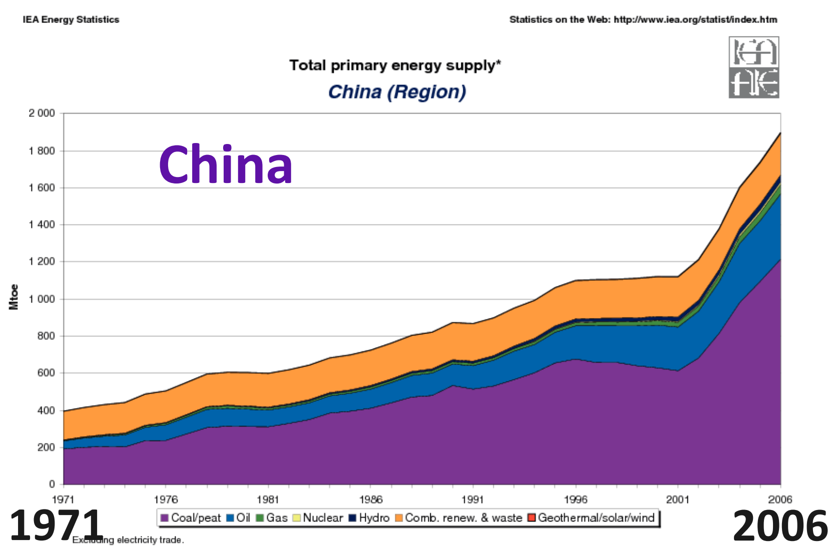


Developing world

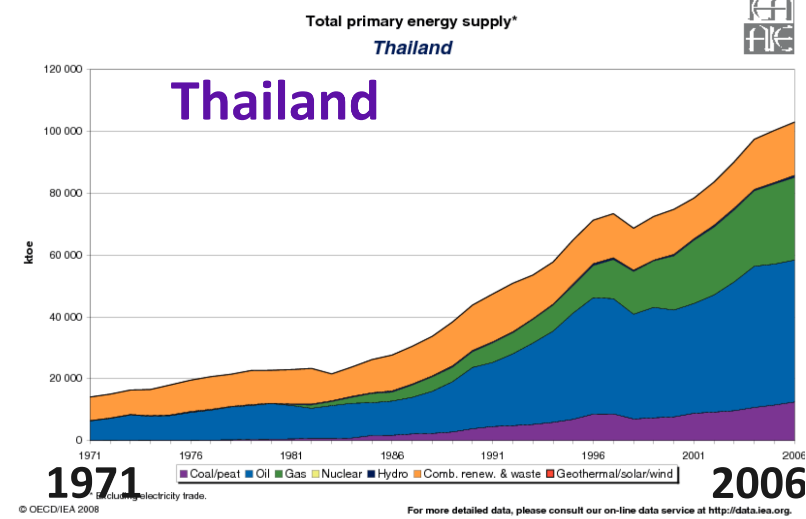


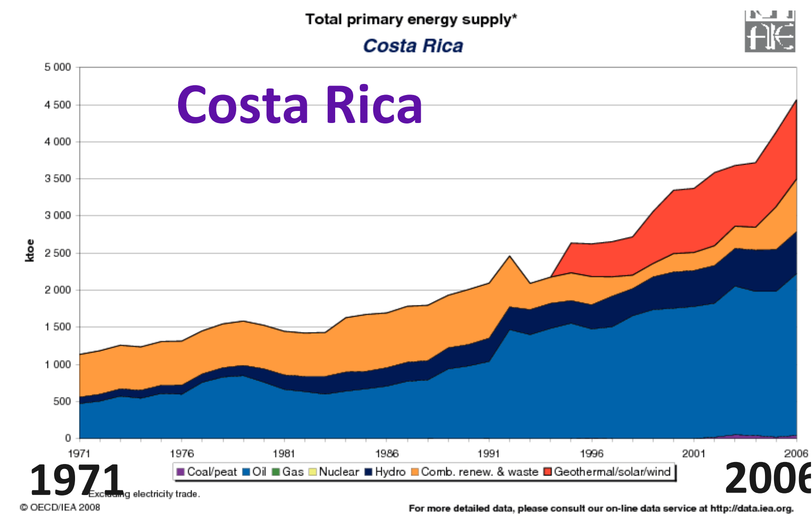
Growth of economy and population fueled By **increased use of fossil fuels**

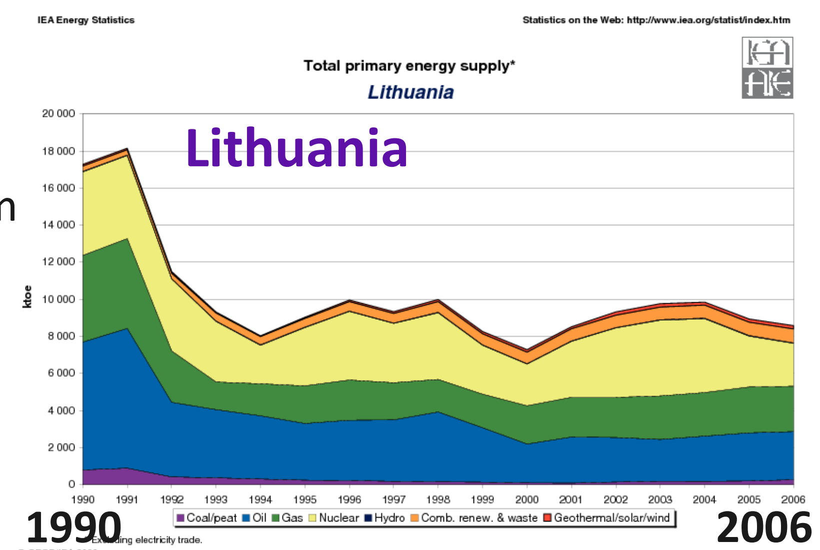
Fossil fuel use growth can be in some cases partially mitigated by use of non-combustion sources.



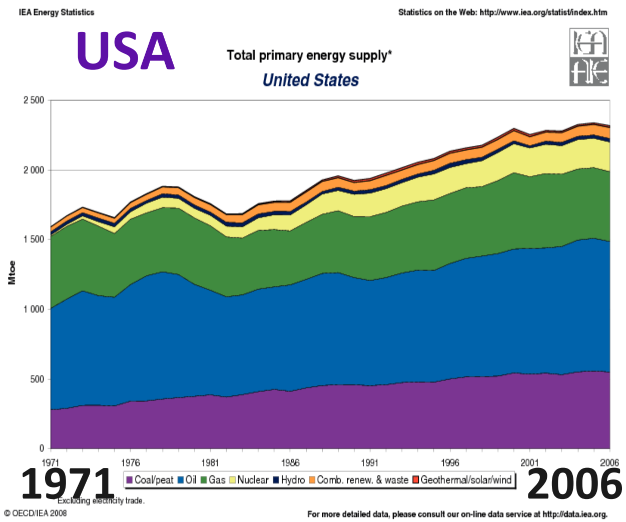
Efficiency gains from replacing soviet system had realized within 5 to 10 years(!!!)

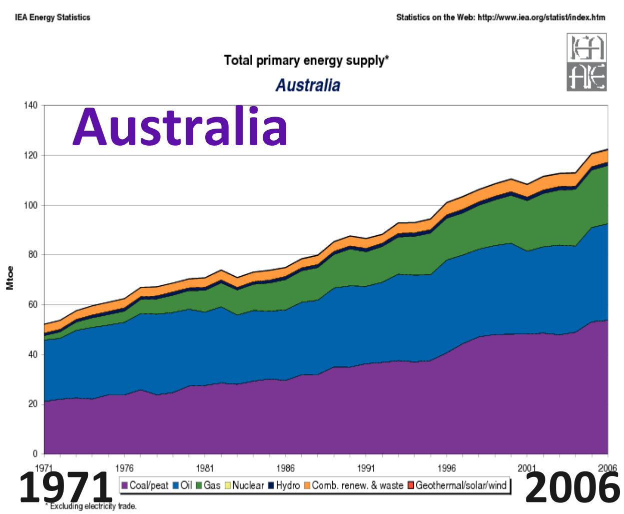


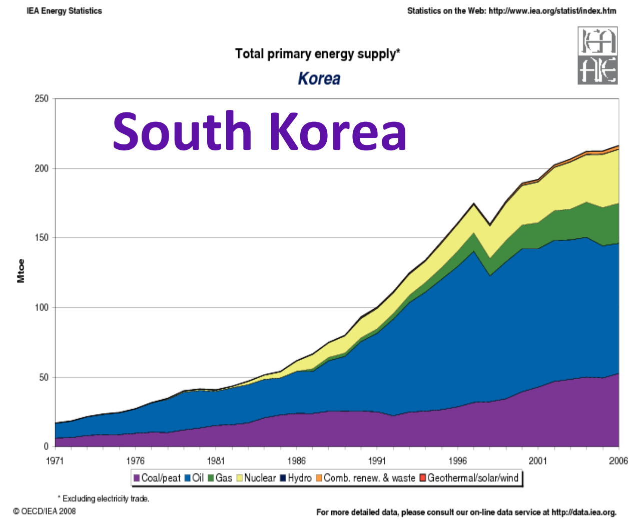


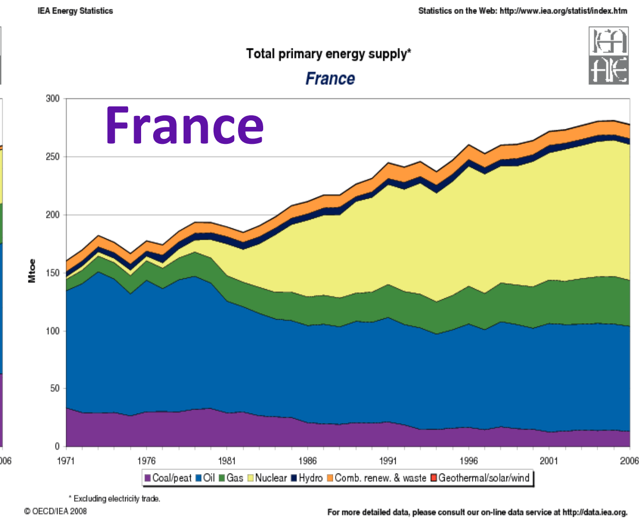


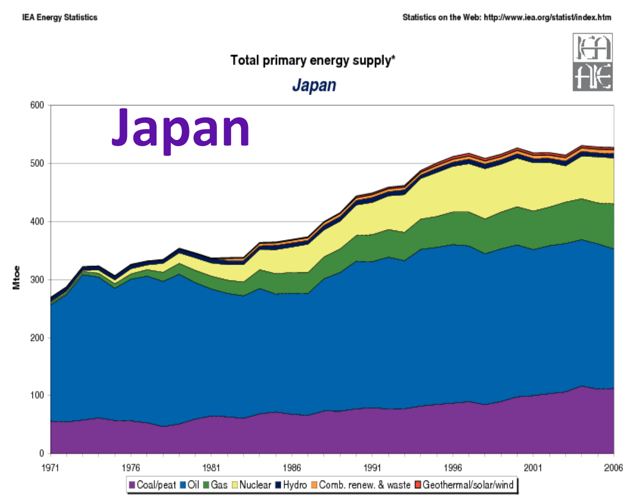
Developed world

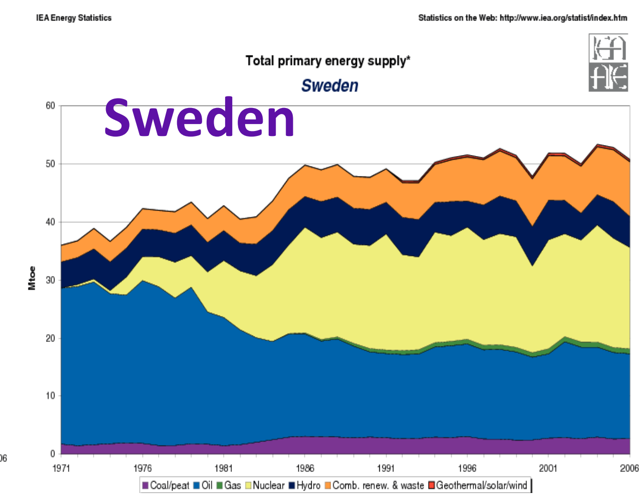


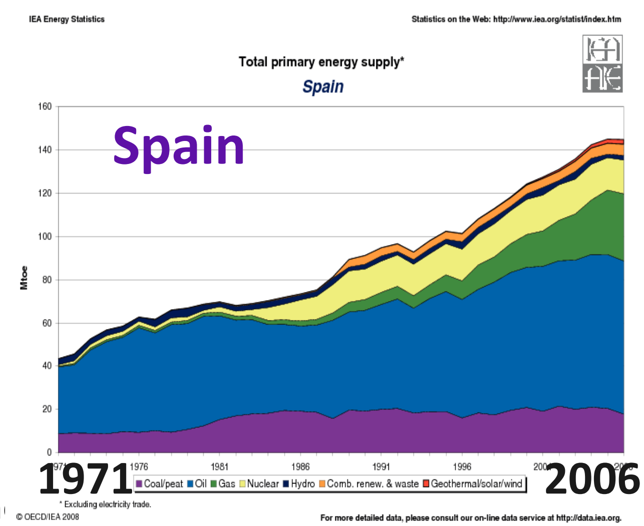


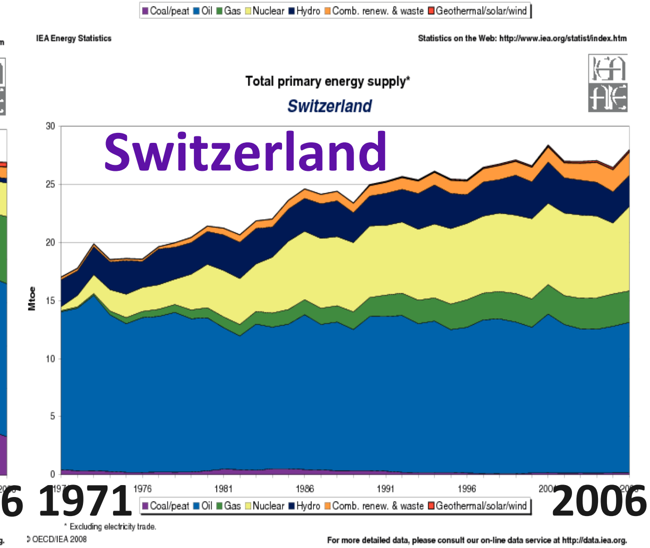




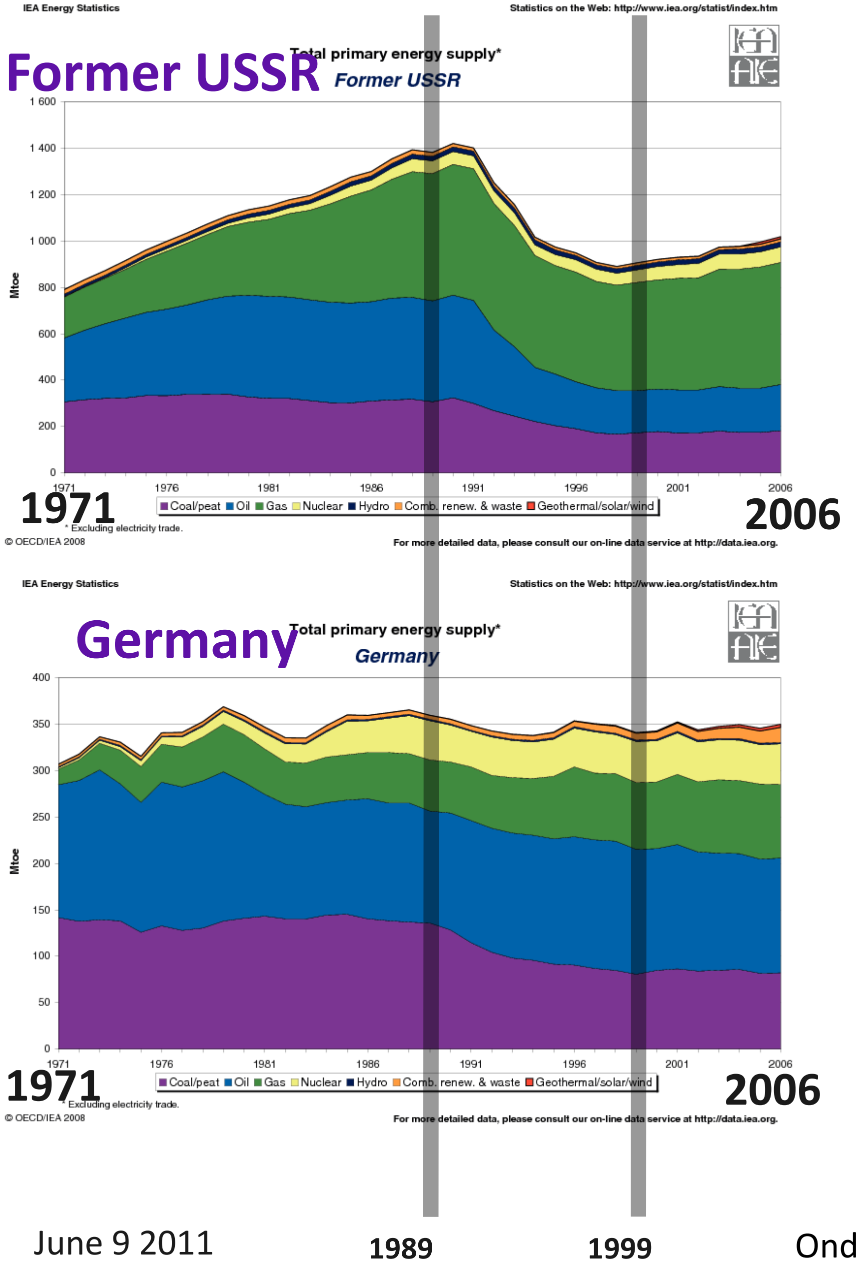


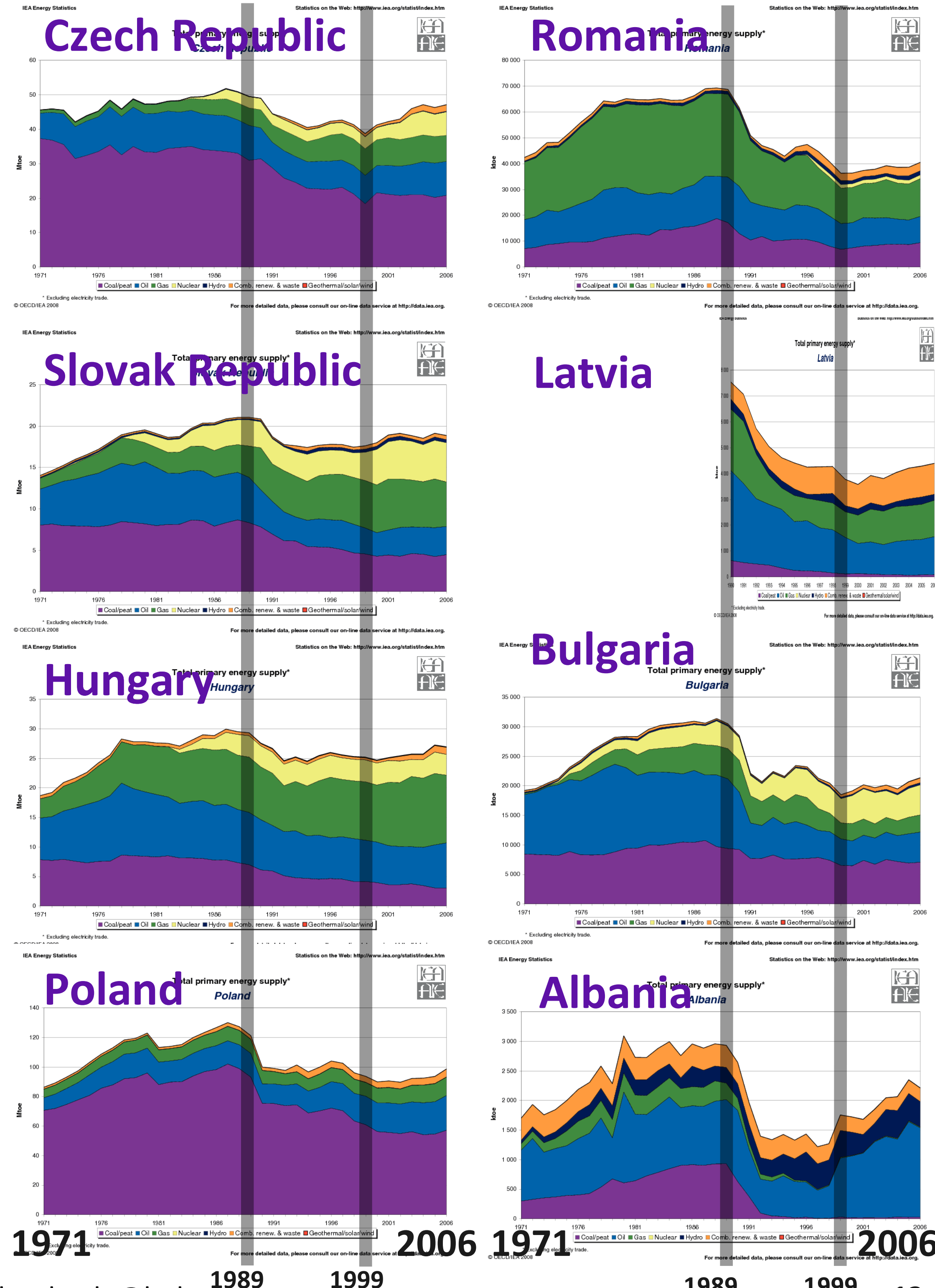






Transition from Soviet economy 1989-1999





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
http://www27.wolframalpha.com/input/?i=177+trillion+cubic+meters+of+natural+gas http://www77.wolframalpha.com/input/?i=1238+billion+barrels+of+oil+in+joules

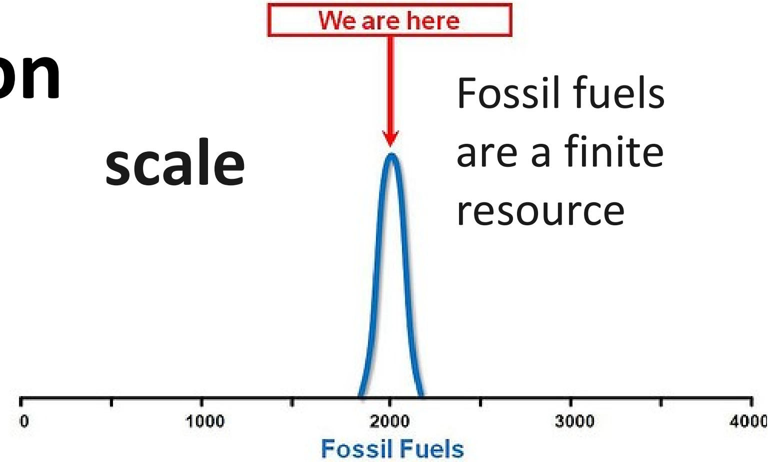
Ratio of **Reserves to Production** gives years of supply at current rate of consumption

Oil: 42 yR/P **7.6 ZJ** of energy
37 % total energy use

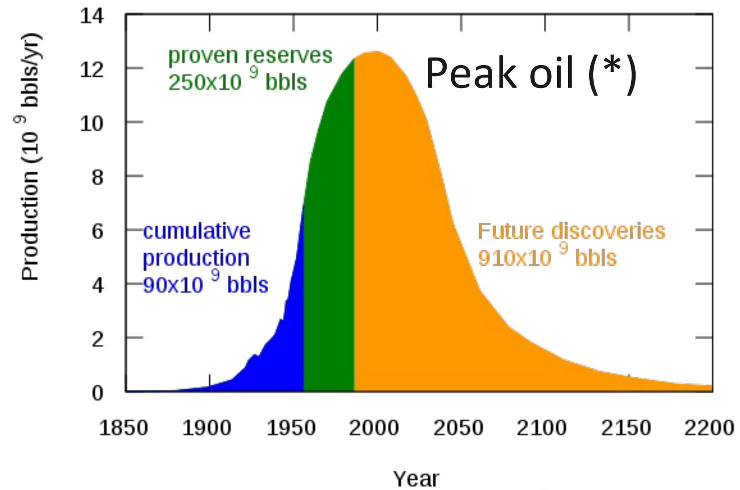
Natgas: 60 yR/P **6.6 ZJ** of energy
23 % total energy use
"Abundant"???

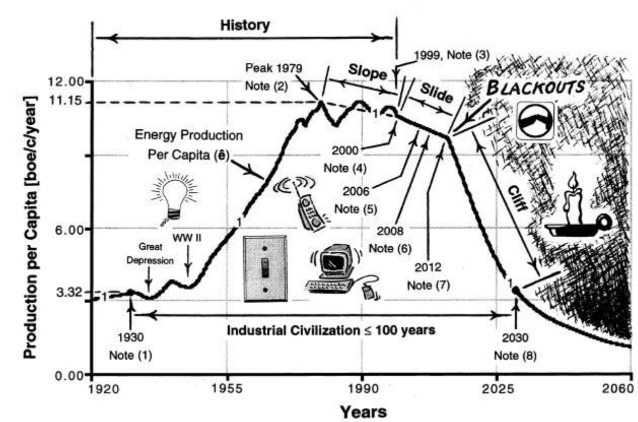
Coal: 133 y R/P **25 ZJ** of energy
USDoE Secretary Dr. Chu's
"worst nightmare"
Needs to be eliminated by 2030 to prevent runaway climate change [J. Hansen et al.]
http://www.columbia.edu/~jeh1

scale



Fossil fuels are a finite resource



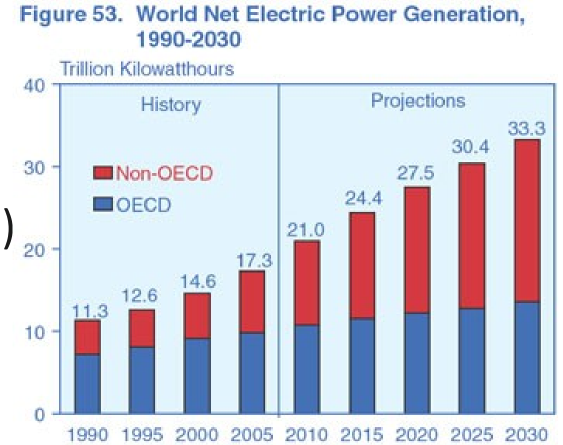


(*) for Peak Oil see recent overview Pedro de Almeida, Pedro D. Silva, The peak of oil production--Timings and market recognition,
Energy Policy, Volume 37, Issue 4, April 2009, Pages 1267-1276, ISSN 0301-4215, DOI: 10.1016/j.enpol.2008.11.016. (http://www.sciencedirect.com/science/article/B6V2W-4VC744G-2/2/4090d8bfe324ad1abf44166f357a69f9)

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

Pollution, Associated risks, Sustainability

Electricity – flexible energy



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).

Electricity – the most versatile kind of energy, efficiently transformable to other forms (heating, colling, motion; powering factories, lights, computers …)

Electricity consumption is rising

- Developed countries – electrify transportation, synfuels
- 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

Ondřej Chvála, chvala@bnl.gov

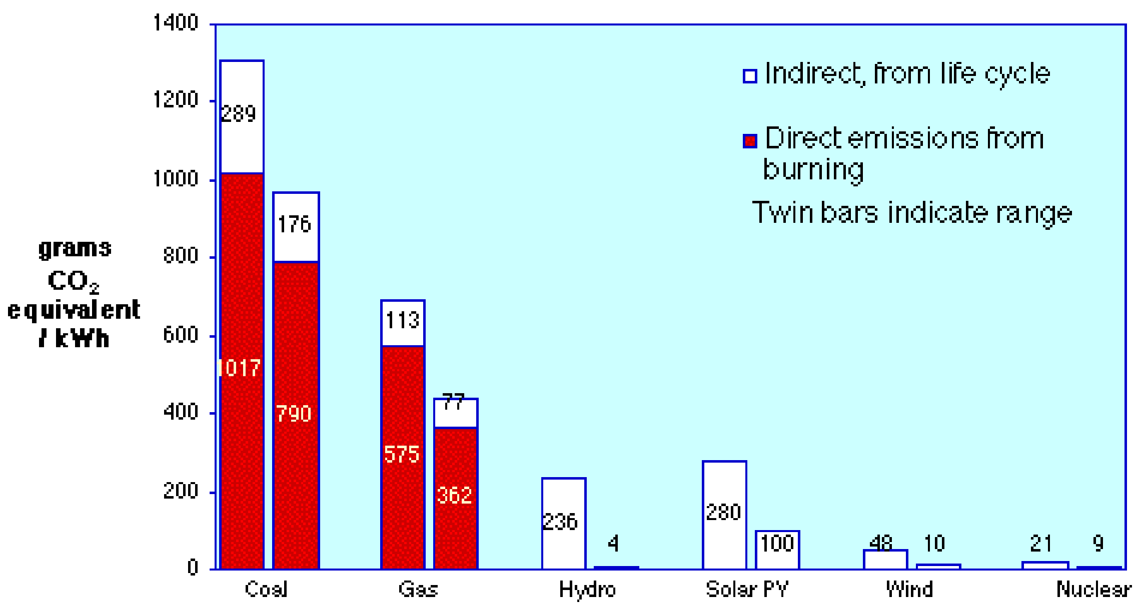
Emissions

Climate Change – emissions of Green-House Gases (GHG) from human activities are the major contributor

40% of US CO_2 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

SO_2, 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

Externalities

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)

Average [USD cents]	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
combustion	8.6	4.6	6.6	2.0		1.8			
non-combustion					0.5		0.6	0.8	0.2

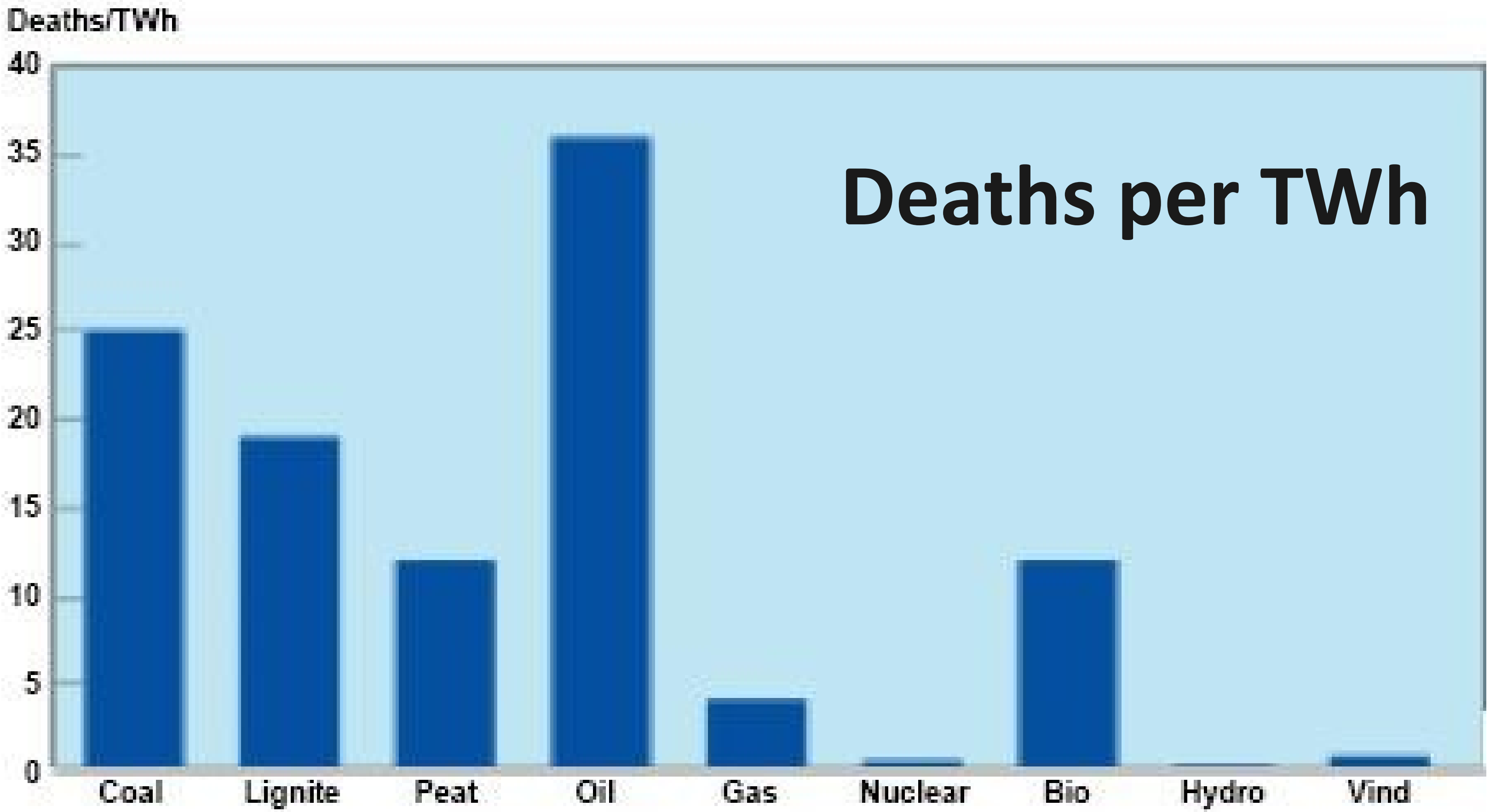
Including the external price would double production cost

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

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

Every industrial scale activity is somewhat unsafe

Risks can be measured



Non-combustion sources of energy are much safer!

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 mortally 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

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

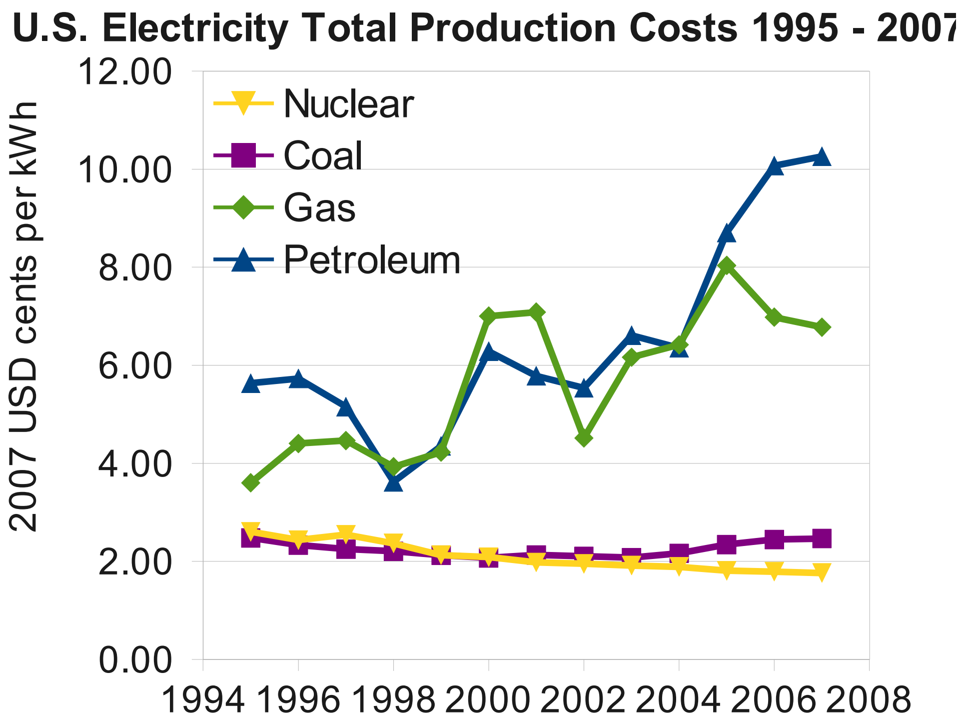
Cost is essential

Price is crucial, esp. for developing world

Cheap Clean energy – otherwise dirty cheap coal

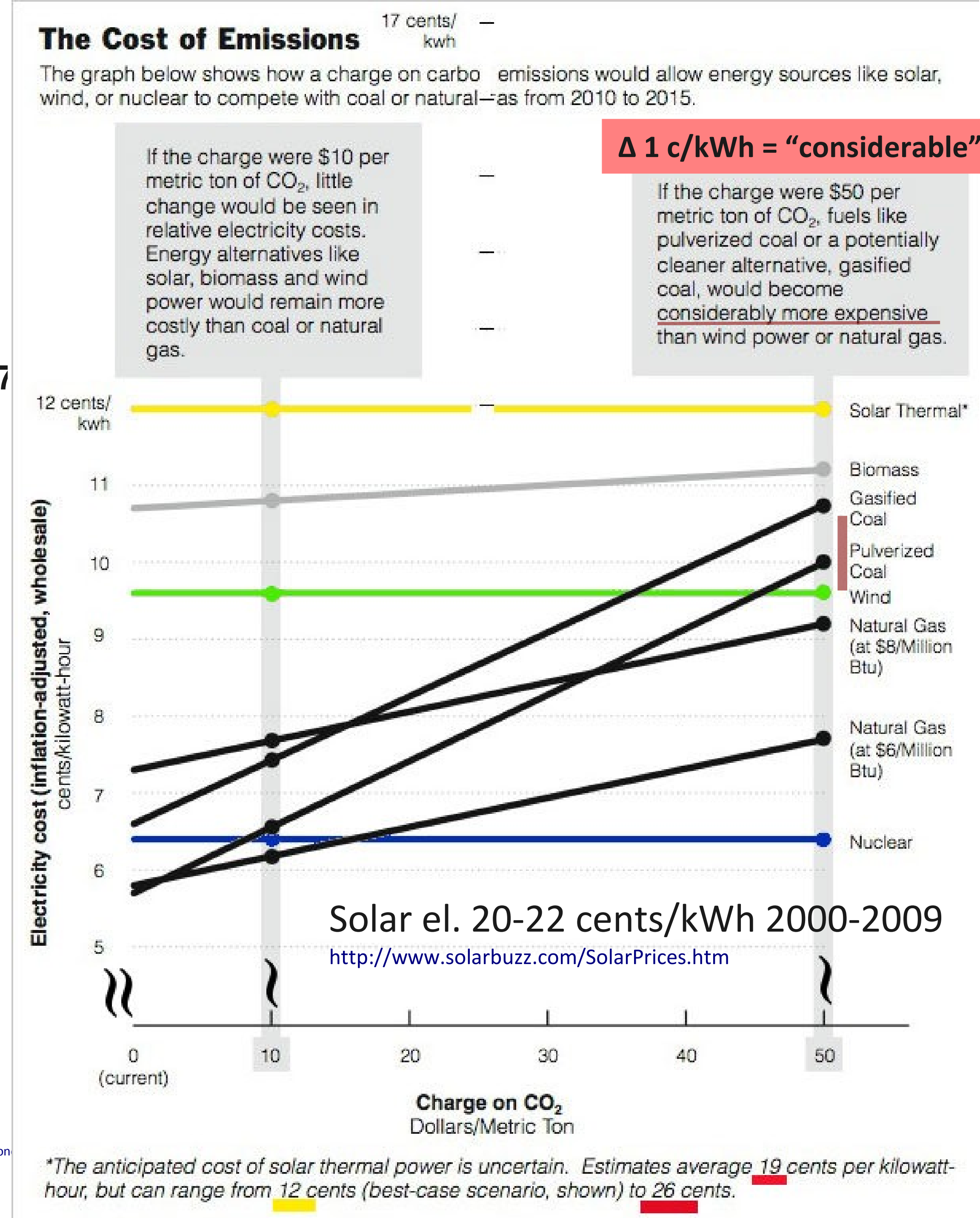
http://theenergycollective.com/TheEnergyCollective/37028

http://www.youtube.com/watch?v=71kckb8hhOQ



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/uselectricityproductioncostsandcompon



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

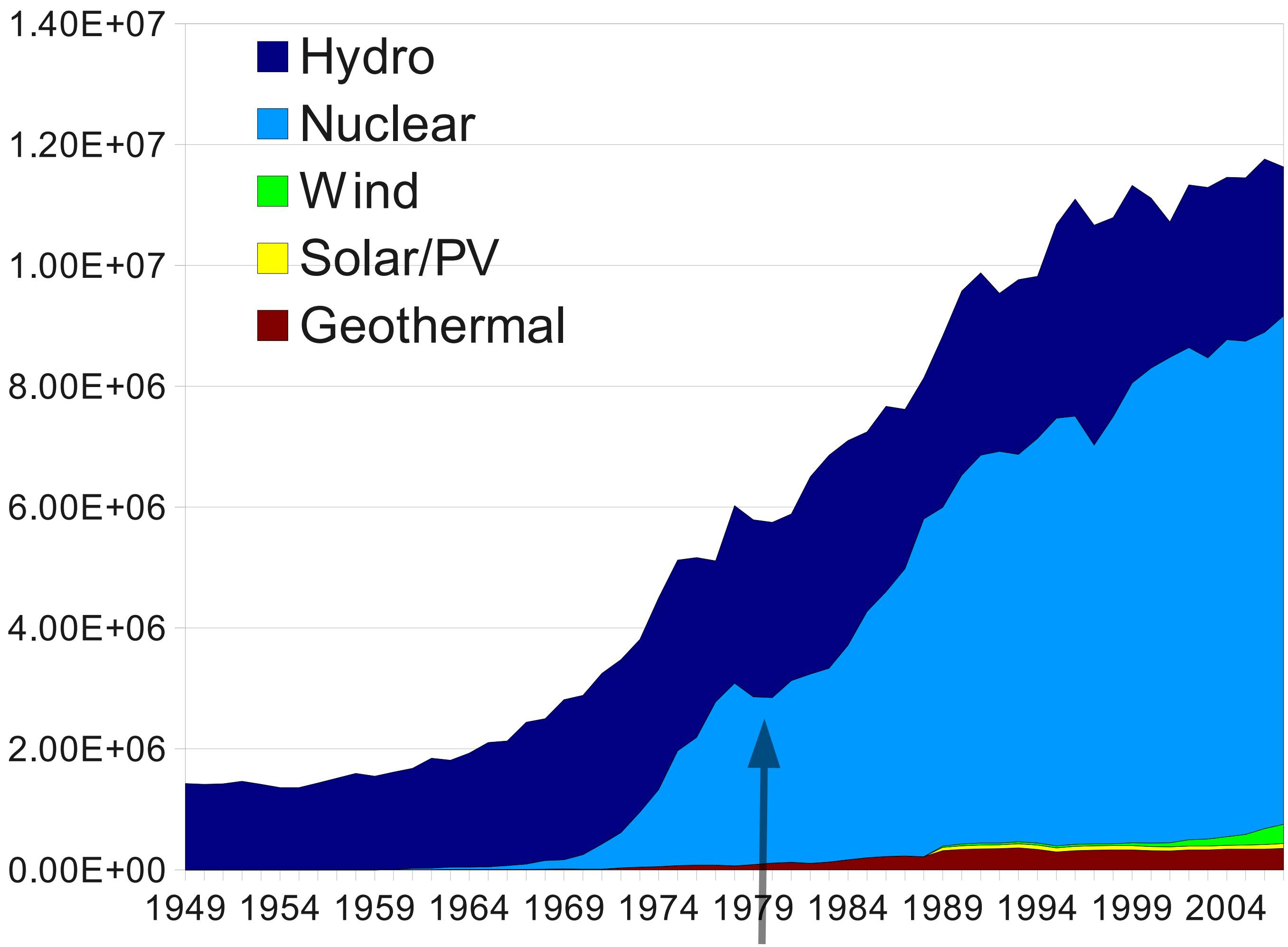
Ondřej Chvála, chvala@bnl.gov

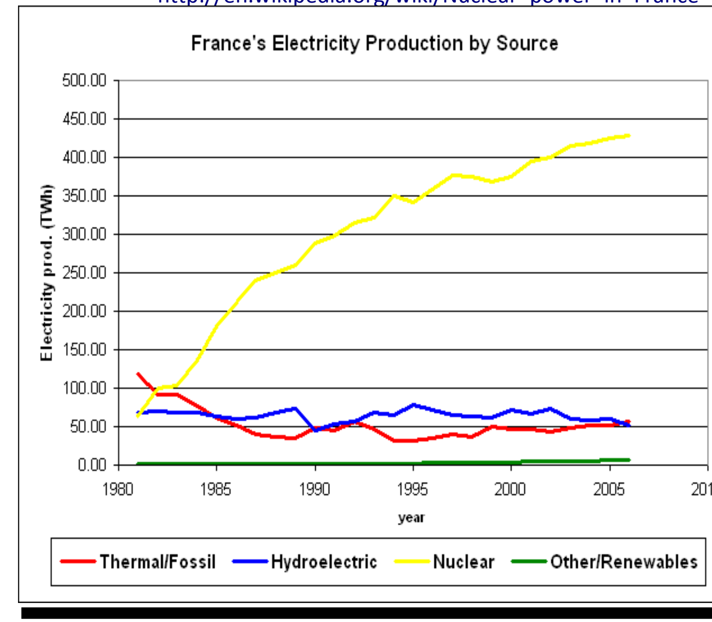
Real Clean energy

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)





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

NB2: **USA EIA 1972** prediction
who killed US nuclear power?
http://www.google.com/search?hl=en&q=smoking%2Bgun+site%3Aat
http://www.21stcenturysciencetech.com/2006_articles/spring%20200
http://atomicinsights.blogspot.com/2009/04/anti-nuclear-effectively-means-pr

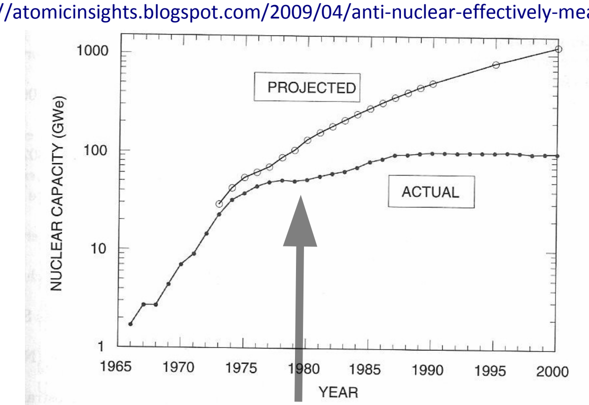
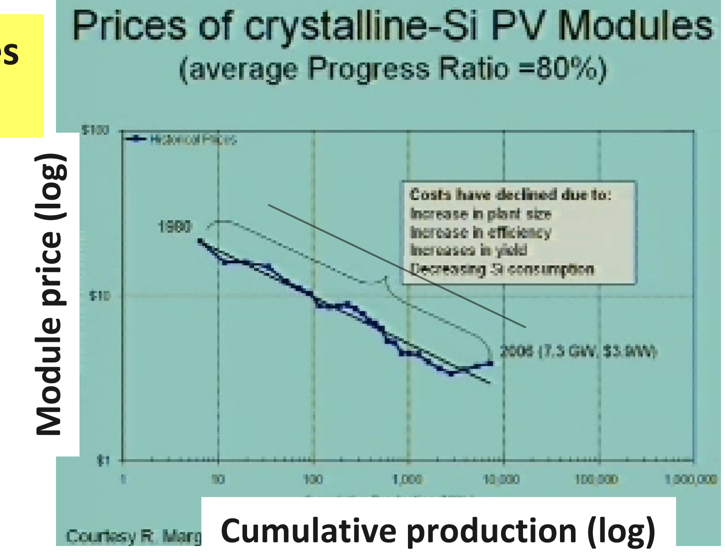


Fig. 2.5. Comparison of U.S. nuclear capacity, projected in 1972 and actual.

Ondřej Chvála, chvala@bnl.gov

Solar energies

Unrealistic with demonstrated technologies
Invest into R&D

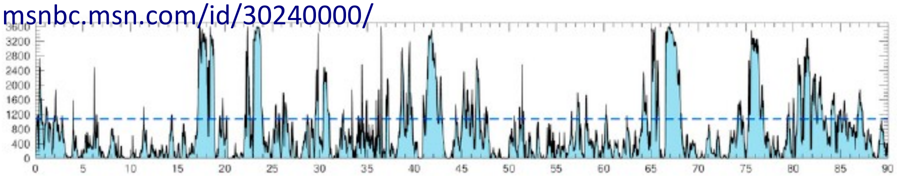


Wind, solar, biomass – the best known (oldest) energy resources
Excellent in particular applications, from calculators to satellites, off grid locations, water pumping, bio-waste use, passive solar heating, ...

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/

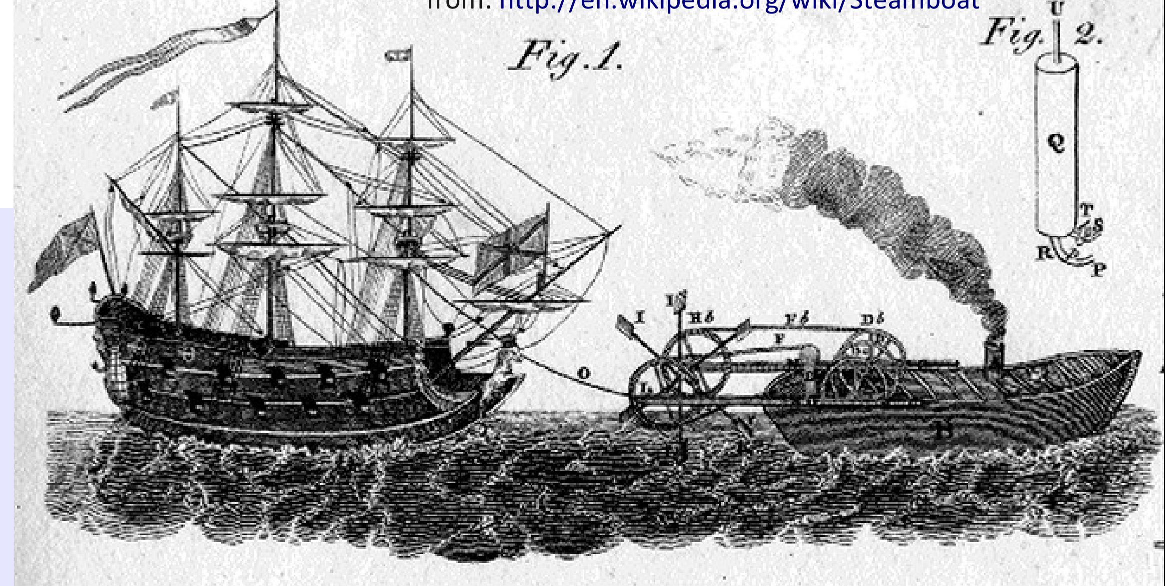
Mass production issues: toxic pollution from PV panel production ($SiCl_4$) in China
http://www.treehugger.com/files/2008/03/solar_pollution_china.php
http://www.washingtonpost.com/wp-dyn/content/article/2008/03/08/AR

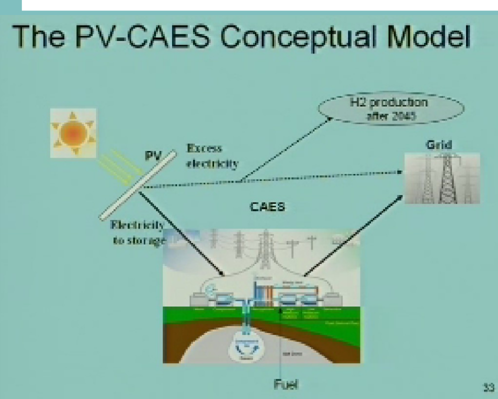


Distribution grid: electricity in = electricity out
Chaotic wind locks in future natgas demand
http://comste.gov.ph/content.asp?code=292
http://www.vtt.fi/inf/pdf/publications/2004/P554.pdf
Similarity **CAES**: natural gas fired "storage"

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

from: http://en.wikipedia.org/wiki/Steamboat





Real energy storage R&D needed (also EVs)

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

"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 Nord Stream build by Gazprom (51%) led co.
- Gerhard Schroeder – chairman of the shareholders committee
- Joschka Fischer – adviser to Nabucco natgas pipeline

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

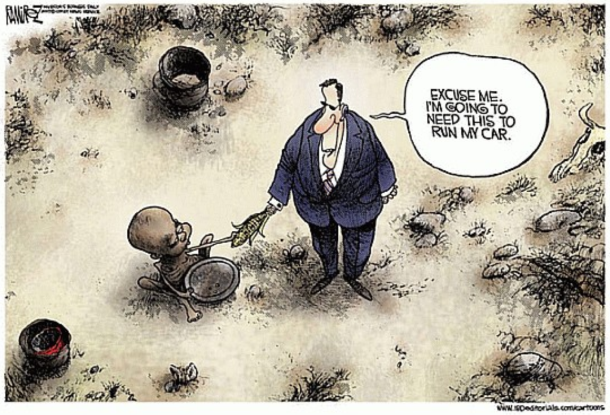
Austria – replaced Zwentendorf NPP by Dürnrohr coal burner

- 4 600 MW in natgas burners in construction or planned.
- Electricity imports 10% and rising

France, **Sweden**, etc. demonstrated than nuclear works to 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://www.wsws.org/articles/2006/apr2006/schr-a14.shtml
http://www.wsws.org/articles/2009/jul2009/fisc-j03.shtml
http://www.washingtonpost.com/wp-dyn/content/article/2005/12/12/AR2005121201060.html
http://ekonomika.ihned.cz/?m=d&article[id]=20266960

Industrial boifuels = 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 boifules 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 boimass 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.

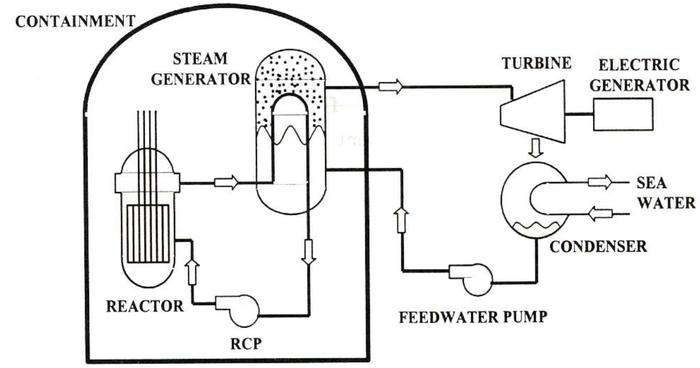
"When a bio-fuel policy is launched in the United States, thanks to subsidies of 6 billion of bio-fuels that drains corn from the market, the foundation is laid for a crime against humanity to satisfy one's own thirst for fuel," Ziegler charged.

Current economic crisis made this problem even worse for the world's poor.

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

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

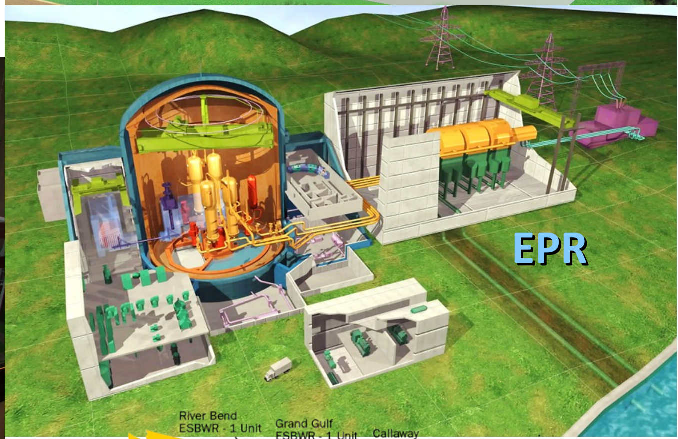
Contemporary nuclear energy



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

Nautilus museum http://www.ussnautilus.org

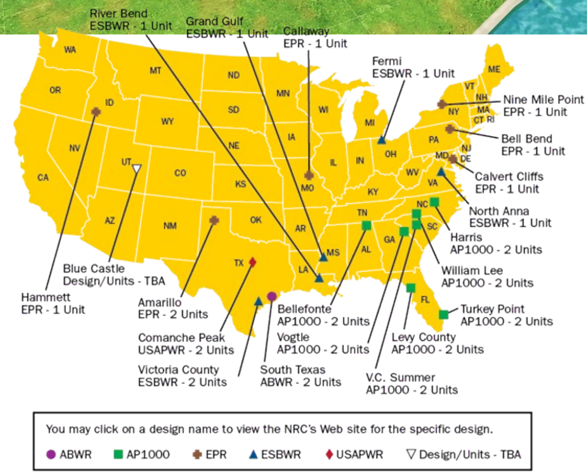
http://en.wikipedia.org/wiki/S1W_reactor



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

World: **441** operating, **60** in construction, **155** ordered/planned, **338** proposed (June 1st 2011)

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

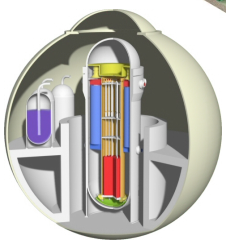


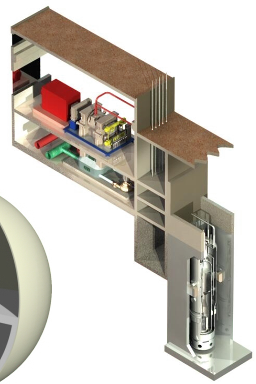
USA: **104** operating, **31** new units in US-NRC pipeline, **26** CoL applications

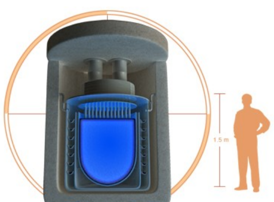
http://www.nrc.gov/reactors/new-reactors.html

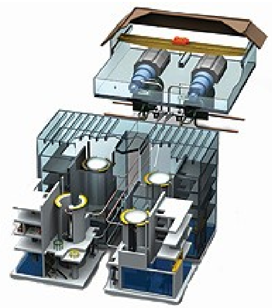
Small modular reactors: Toshiba 4S, Westinghouse IRIS, nuScale PWR, Hyperion, NEREUS, B&W mPower
Regulatory issues to be solved - $4M/year/reactor lic. fee

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
http://www.babcock.com/products/modular_nuclear/









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, Xe, ...)

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 – weapons do not "just happen"

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**

Contrary argument: Nuclear energy reduces (energy) scarcity, reducing the risks of conflicts

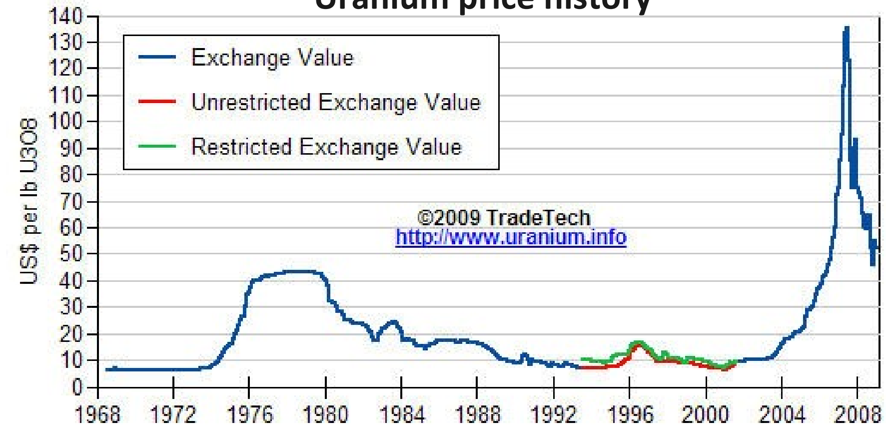
Appropriate regulations of nuclear materials, procedures, and safety necessary for the above
However, nuclear regulators task: minimizing risks from nuclear energy; without considering the risks of not using nuclear energy => stagnation

How much uranium is there?

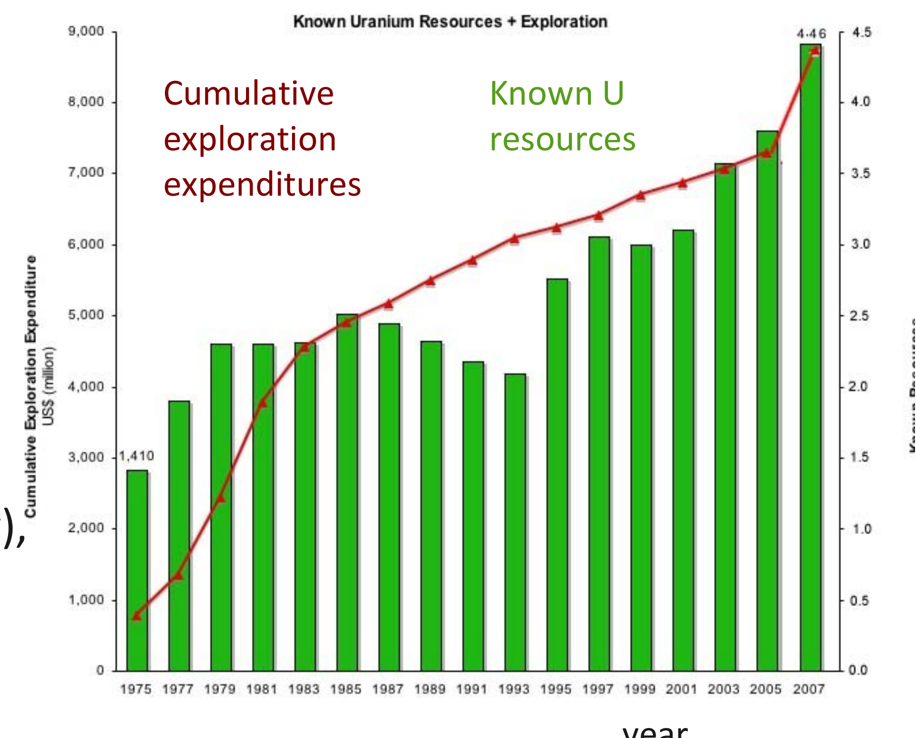
Log-normal uranium distribution

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

Uranium price history



U: Recently used mineral, not fully prospected

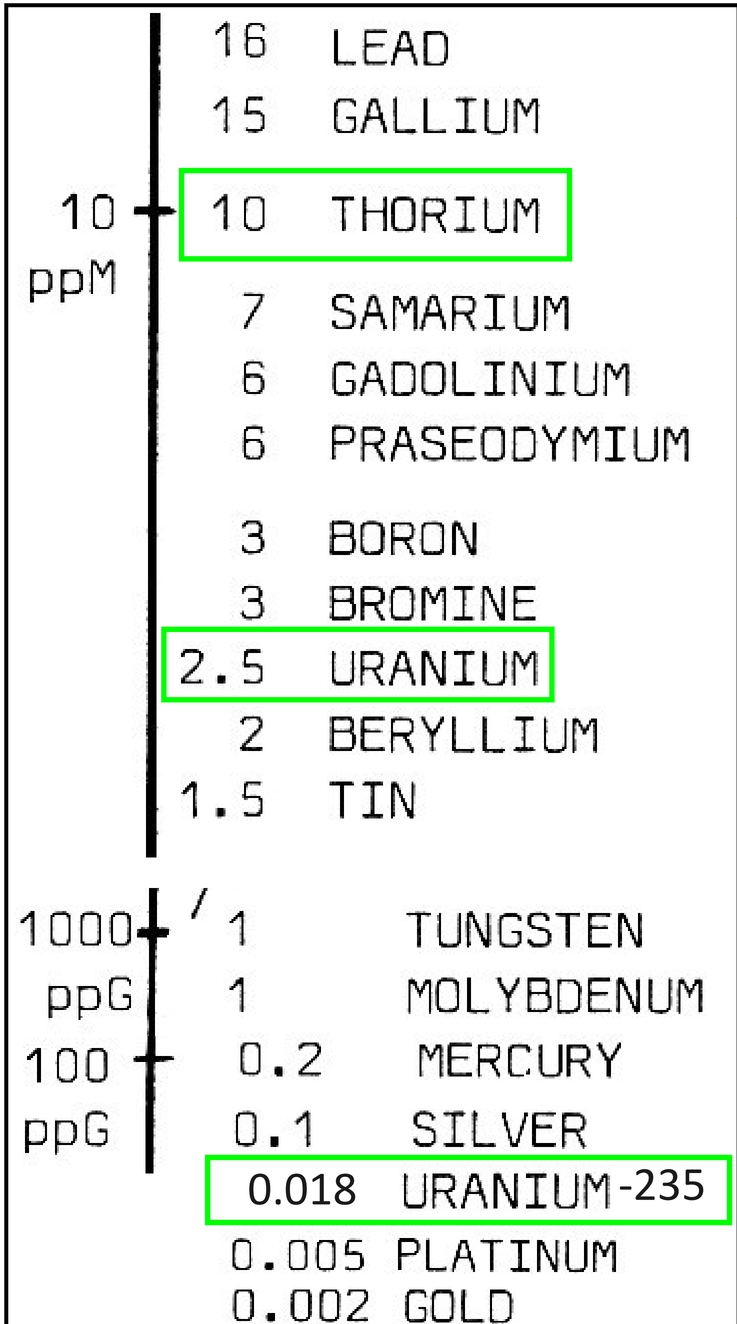


Currently known and estimated uranium resources cheaper than \$130/lb enough for ~80 years at current consumption.

However, scaling up nuclear energy by a factor of 15 (to replace combustion) to 40 (billions of ppl living in poverty), PWR sand once-through fuel 'cycle' - inadequate

References:
http://www.world-nuclear.org/info/inf75.html
http://nuclearinfo.net/Nuclearpower/UraniuamDistribution
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

Thorium and Uranium Abundant in the Earth's Crust



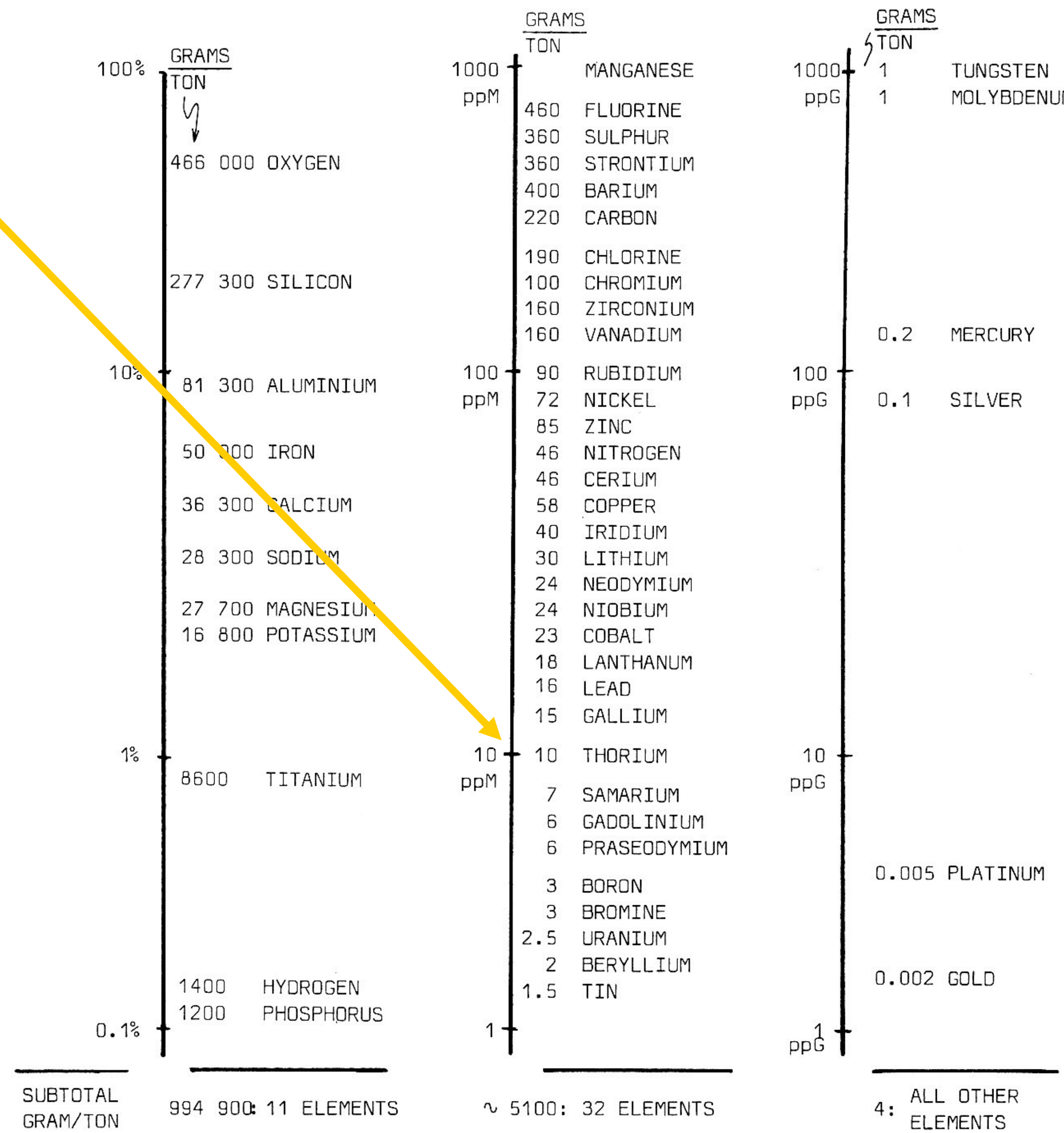
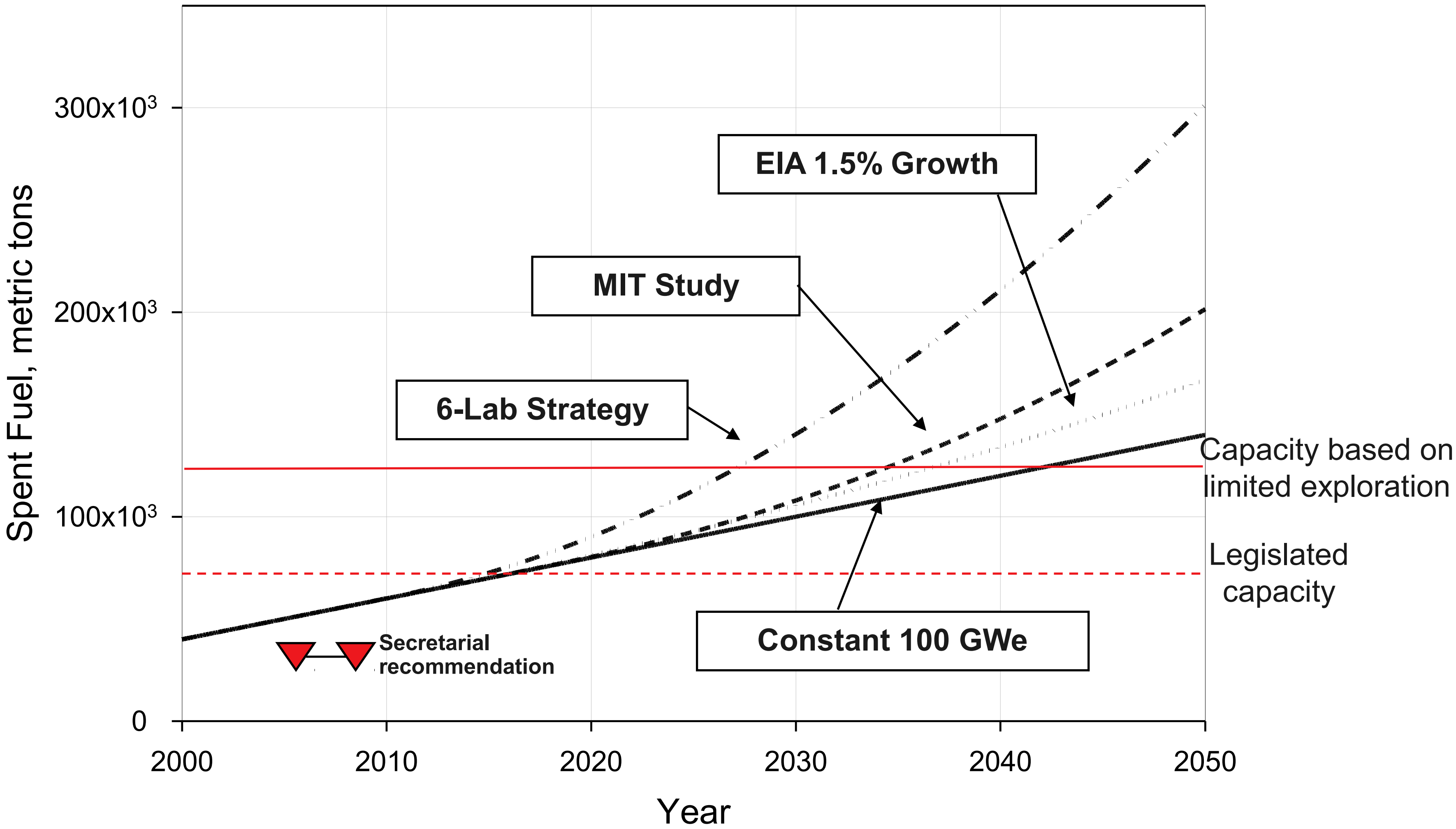


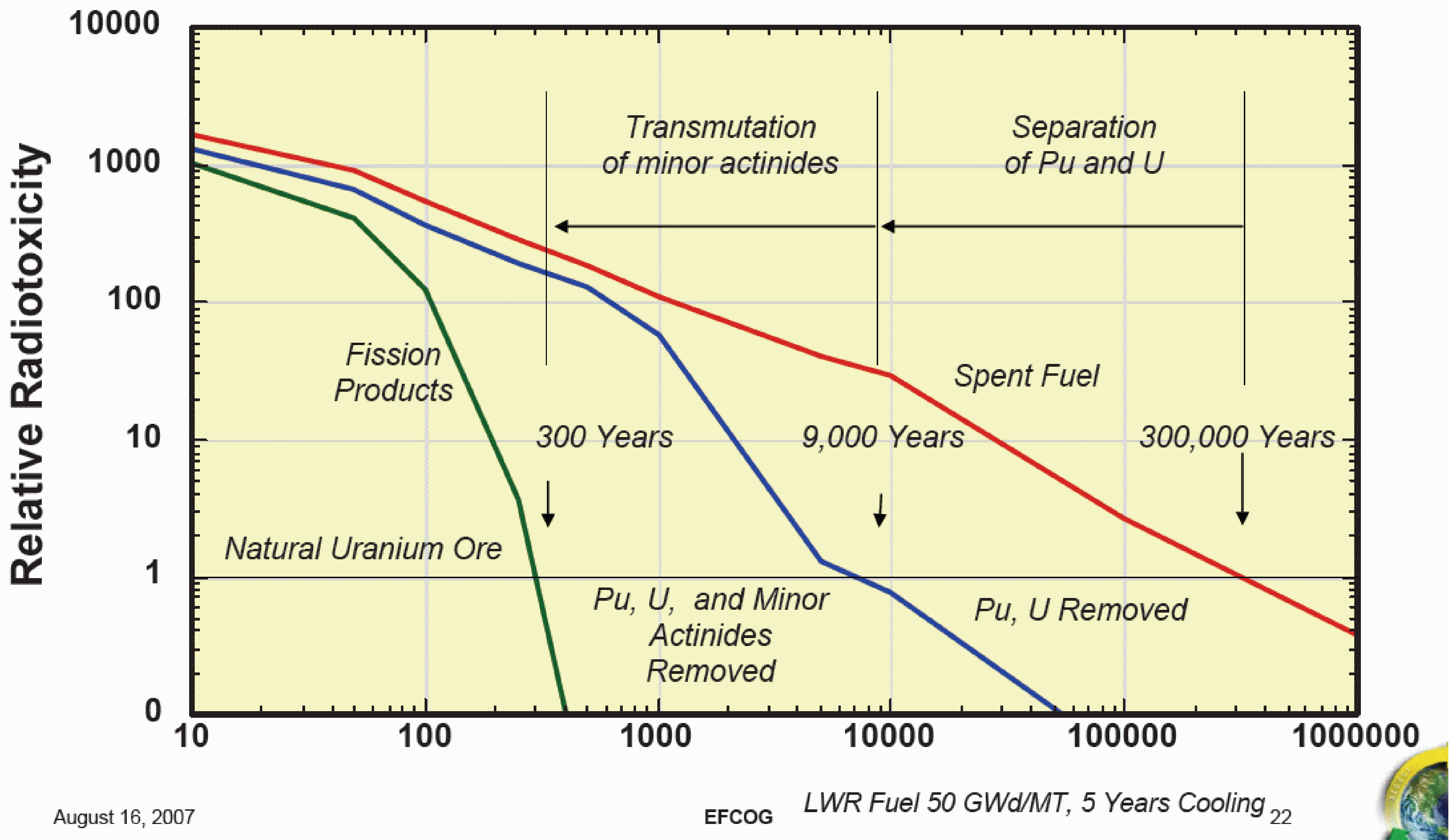
Fig. 5.13. The chemical composition of the Earth's crust.

Projected Spent Fuel Accumulation without Reprocessing



Ondřej Chvála, chvala@bnl.gov

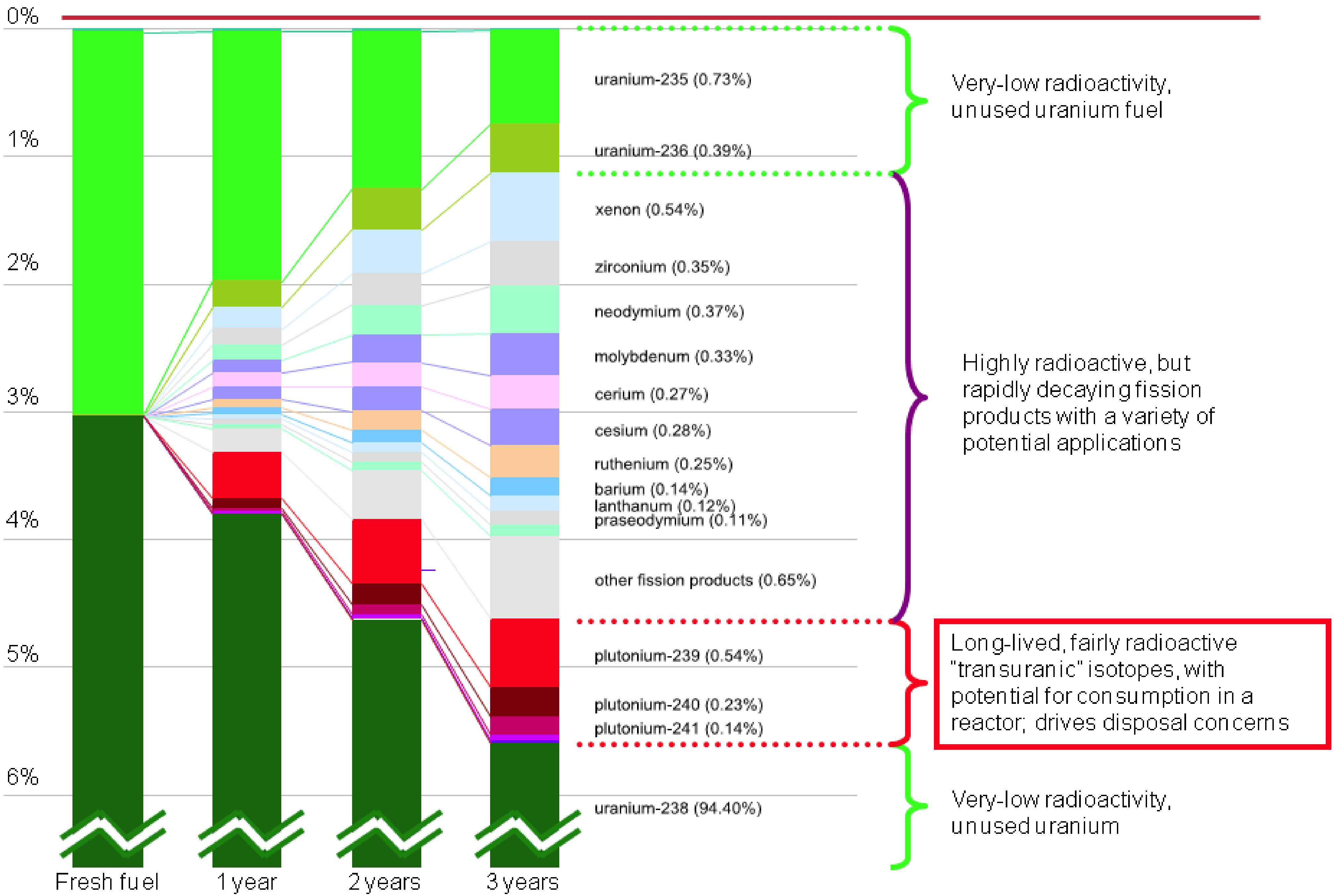
Long-term Radiotoxicity of Fission Products is low



Ondřej Chvála, chvala@bnl.gov

Composition of Conventional Nuclear Fuel

(17x17 Westinghouse, 3% enr., 1100 day irrad, 33000 MWD/MTU, discharge composition, Origen Arp analysis)

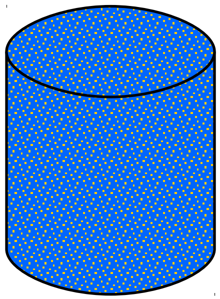


Slide from Kirk Sorensen

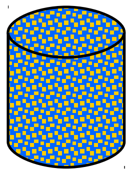
Nuclear fuel cycles

mission: make 1000 MW of electricity for one year

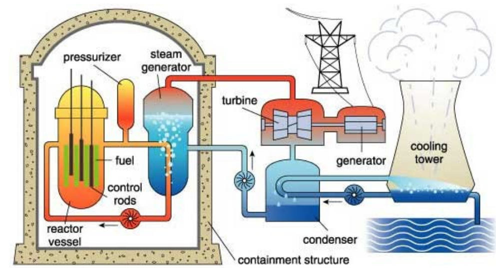
Contemporary nuclear fuel 'cycle'



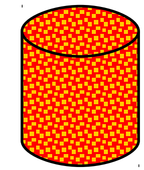
250 t of natural uranium containing 1.75 t U-235



35 t of enriched uranium (1.15 t U-235)



Uranium-235 content is “burned” out of the fuel; some plutonium is bred and burned (1/3 of total burnup)

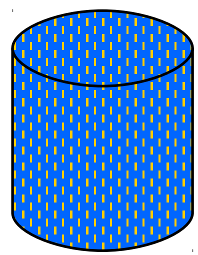


35 t of spent fuel stored on-site until disposal at Yucca Mountain.

It contains:

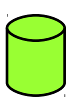
- 1.0 t fission products
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium + M.A.

useful nuclear fuels



215 t of depleted uranium containing 0.6 t U-235—disposal plans uncertain.

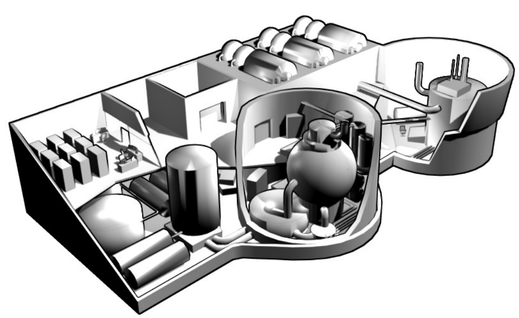
Closed nuclear cycle – ~250x more efficient



One tonne of heavy metal fissile fuel

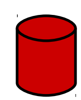
Actinides from spent nuclear fuel, Natural uranium,

Thorium



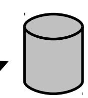
Liquid Metal cooled Fast spectrum Breeder Reactors (LMFBR)

Molten Salt Reactors (MSR)

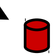


One tonne of fission products; no uranium, plutonium, or other actinides.

Fission products = rare materials with unique properties



Within 10 years, 83% of fission products are stable and can be partitioned and sold.



The remaining 17% fission products need isolation for ~300 years.

Other uses: Tc99 – strong anti-corrosion agent in alloys and coatings; irradiation sources for medicine, industry, sanitation (destroy complex halides in waste water treatment); valuable catalysts (Ru, R, Pd), Xe for ion engines

Ondřej Chvála, chvala@bnl.gov

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 (Superfenix → 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 <80 reactors, Not that high temperature for direct heat utilization (550 C = 1022 F), Public Perception, Complicated active controls, Net breeding (used to be advantage) may be problematic, Cost?

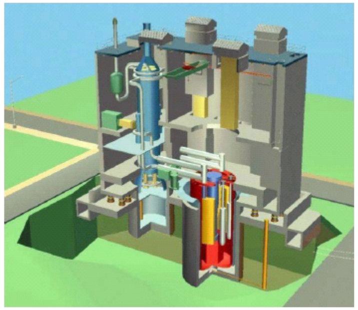
Fast reactor summary references:
http://www.world-nuclear.org/info/inf98.html
http://www.world-nuclear.org/info/inf08.html

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

Uranium resource with closed cycle:
http://www-formal.stanford.edu/jmc/progress/cohen.html
http://sustainablenuclear.org/PADs/pad11983cohen.pdf

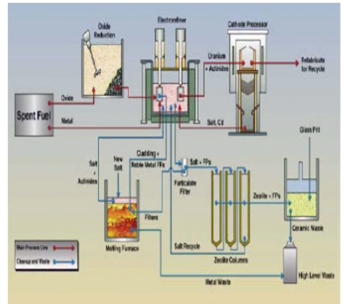
SuperPhenix
http://en.wikipedia.org/wiki/Superph%C3%A9nix
http://lpsc.in2p3.fr/gpr/sfp/superphenix.html

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

imagination at work

3
GE
2/15/2007

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

imagination at work

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/MWhr

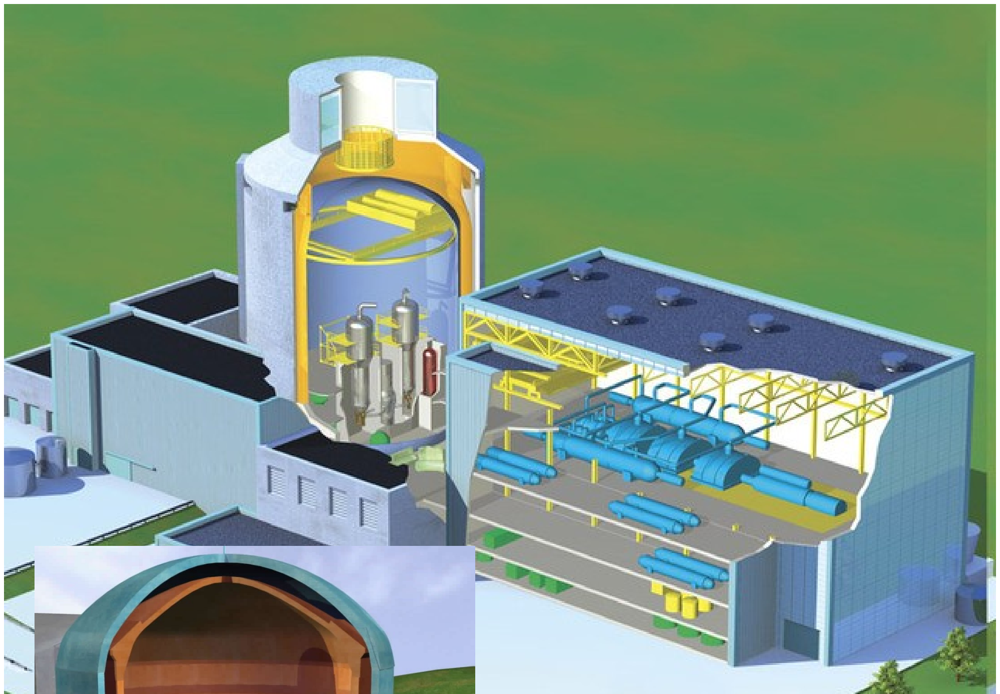
Timeline: within 5-15 years fuel qualification program with a test reactor

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

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

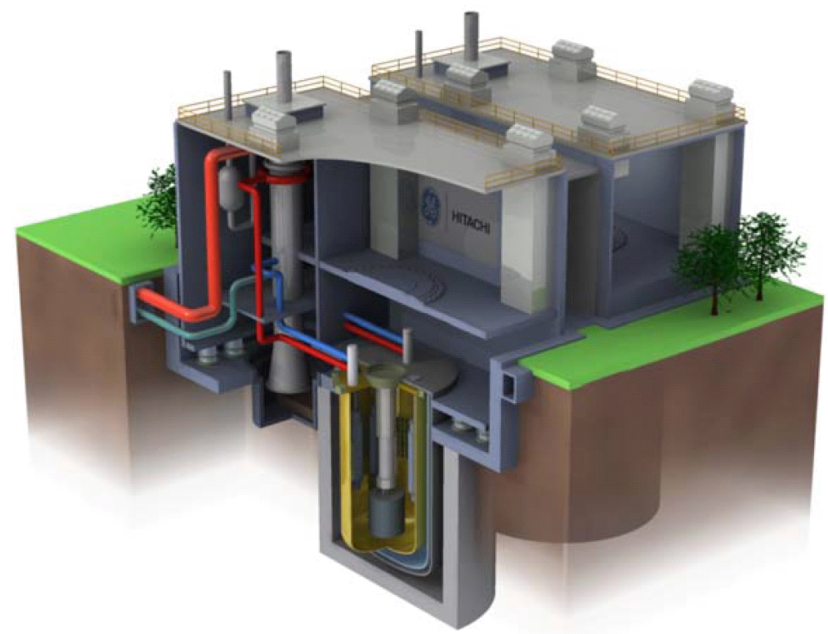


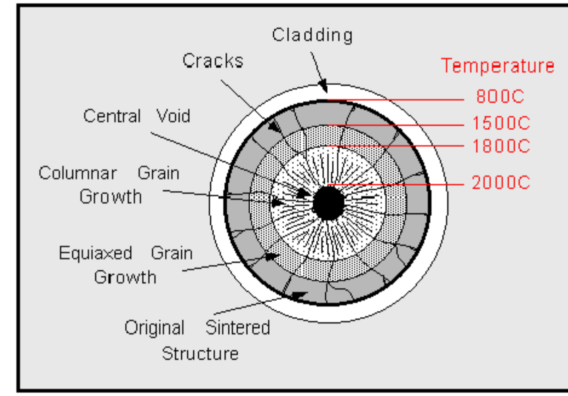
Figure 2: PRISM Reactor power block used to produce electricity from spent nuclear fuel.

Molten salt reactors and Thorium

- We need better nuclear power than 60 years old designs conceived to power submarines, which can address issues such as:
  - Resource efficiency, spent nuclear fuel “waste”, safety, scalability, upfront cost
- MSRs can address that as I will argue in the following section
  - General characteristics of MSRs
  - Historic overview of MSR development
  - Notable technical details
  - Current status of development

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. Xenon poisoning, waste accumulation or complicated reprocessing.



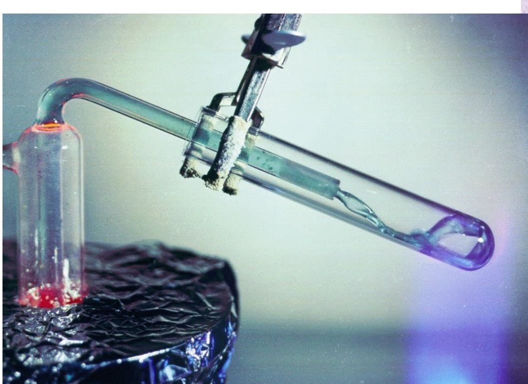
__Fluid fuels__, in particular **__molten fluoride salts__** – ionic bonds; Thorium

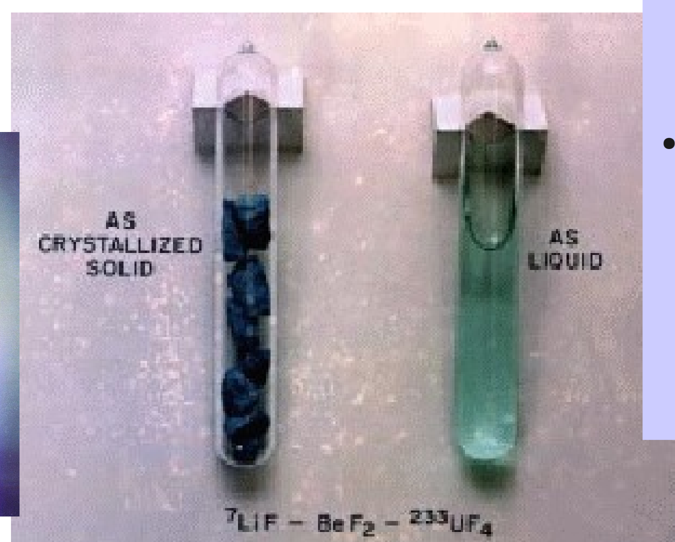
The birth of the Liquid Fluoride Reactor

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 much easier in fluid form
  - Poison buildup reduced, breeding enhanced
  - "A pot, a pipe, and a pump…"
  - Whole new landscape of possible reactor geometries

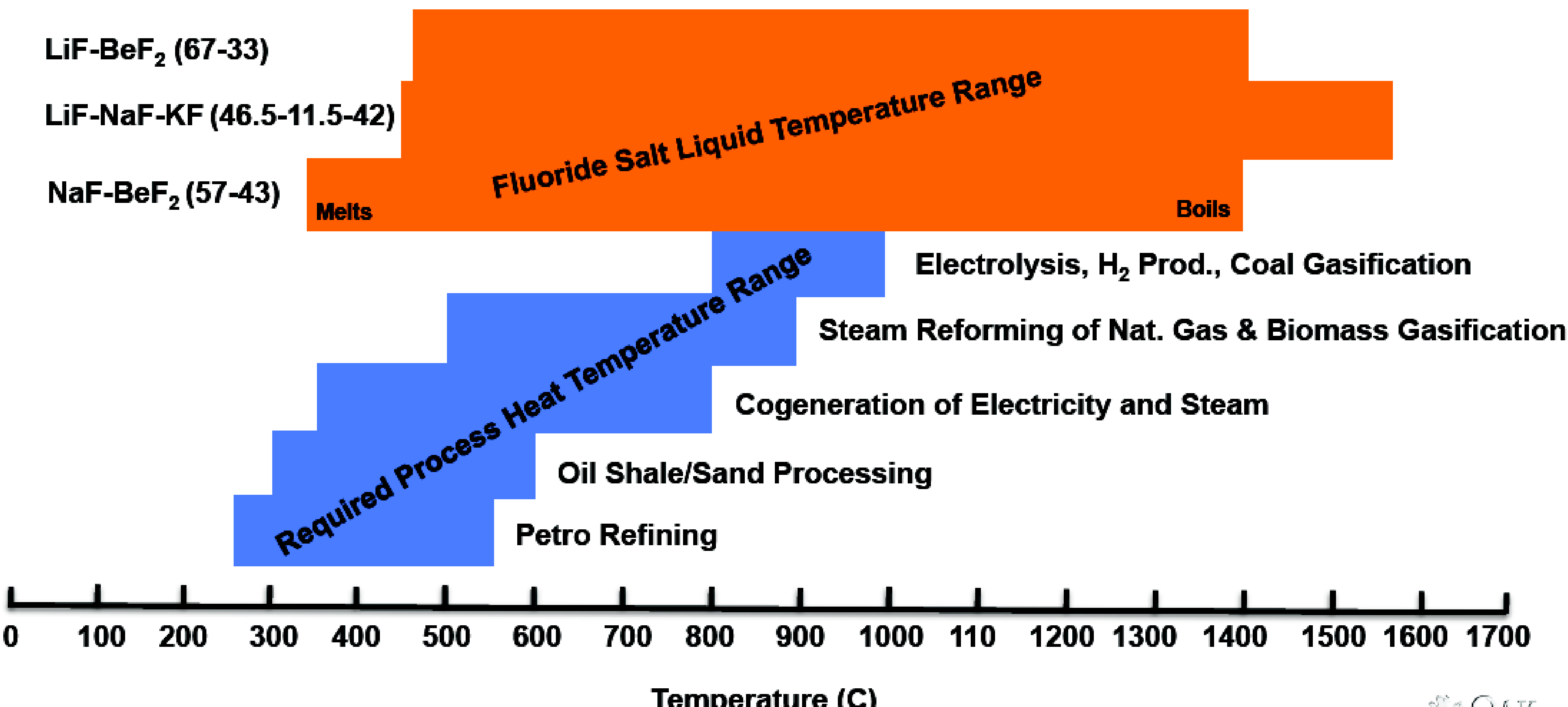




Fluoride salts: superb heat transfer medium

Molten fluoride salts are noncorrosive, transparent, operate at atmospheric pressure, are non-reactive, have huge liquid range, are superior coolants (4x vol. heat capacity [J/m^3] of sodium → smaller HXs);
Can be used as coolants for PBMR/AHTR/FHR instead of He
core power density ~30 MWth/m^3 versus 4.8MWth/m^3 for He coolant → smaller reactor
TRISO max. fuel temperature during accidents reduced from 1600C to 1100C
4x reduction in spent fuel volume

Operating temperature windows of salts fit well with industrial needs



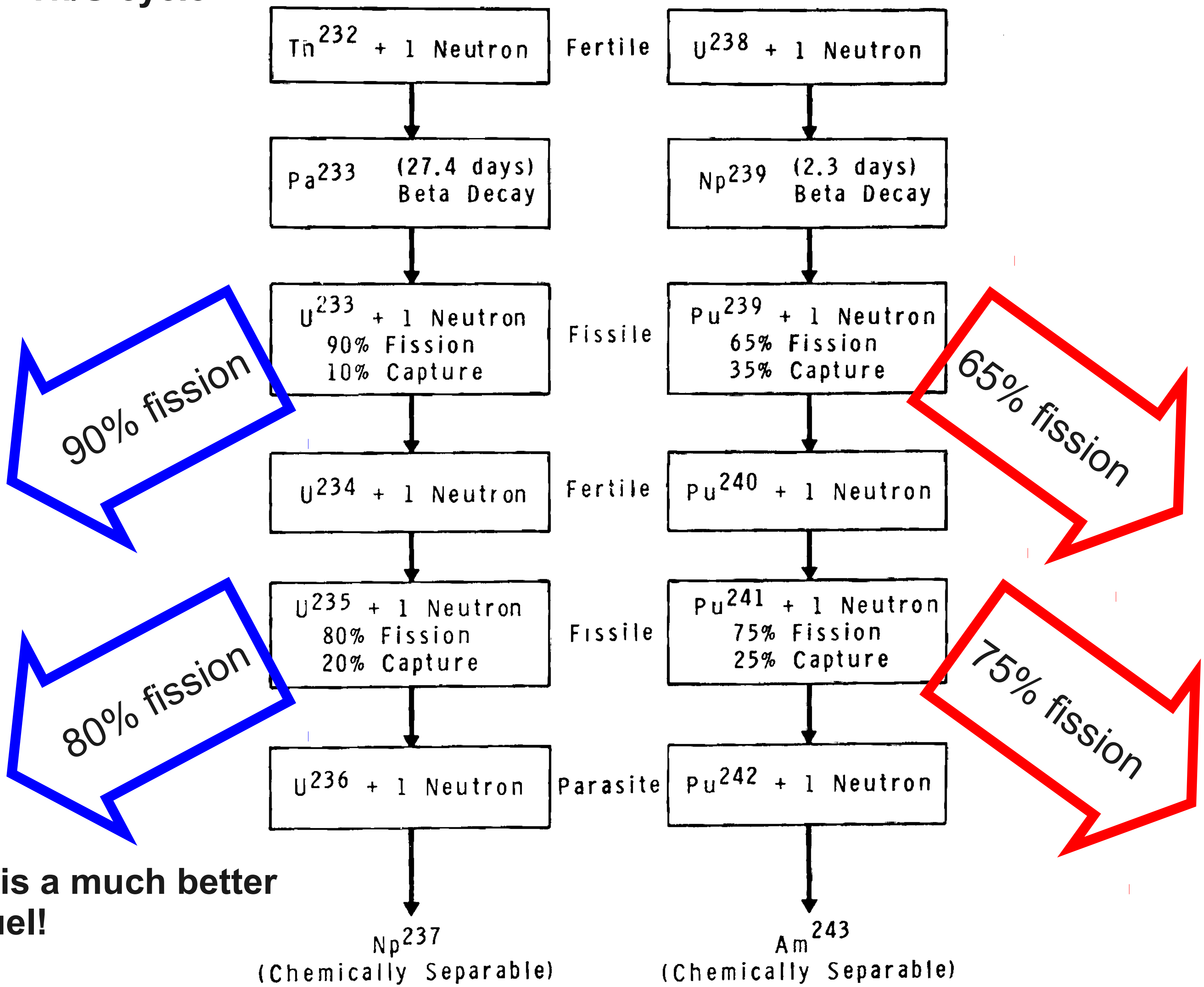
OAK RIDGE National Laboratory

S. R. Greene, 18 Jun 10

Why thorium?

Th/U cycle

U/Pu cycle



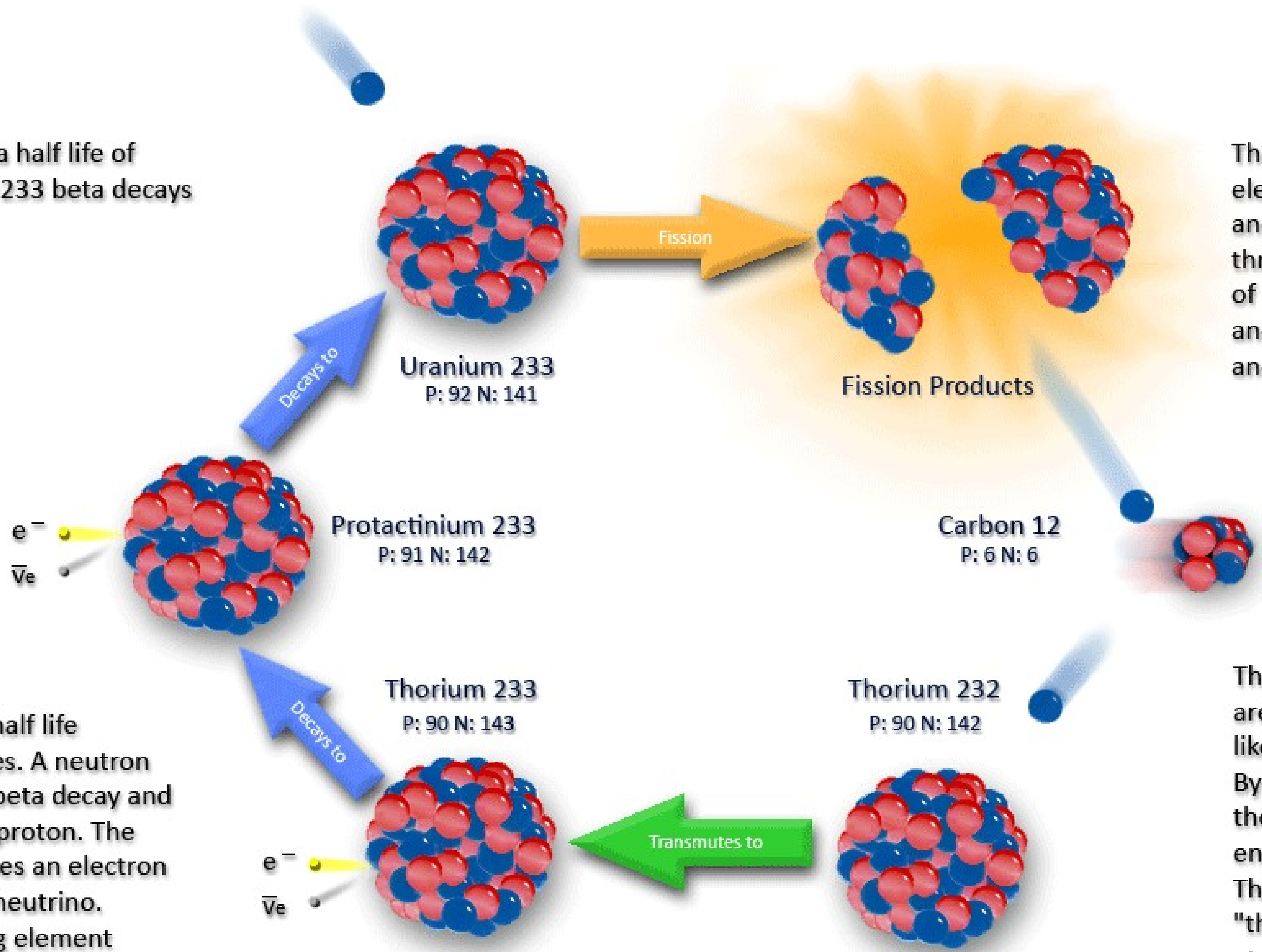
Thorium is a much better fission fuel!

An Introduction to the Thorium Fuel Cycle

U-233 captures a neutron and fissions. When the atom fissions it generates 198 MeV of energy.

Pa-233 has a half life of 27 days. Pa-233 beta decays to U-233.

The nucleus splits into two new elements of unequal size, one heavy and one light. In addition, two or three neutrons are released. Many of these elements such as xenon and neodymium can be collected and sold.

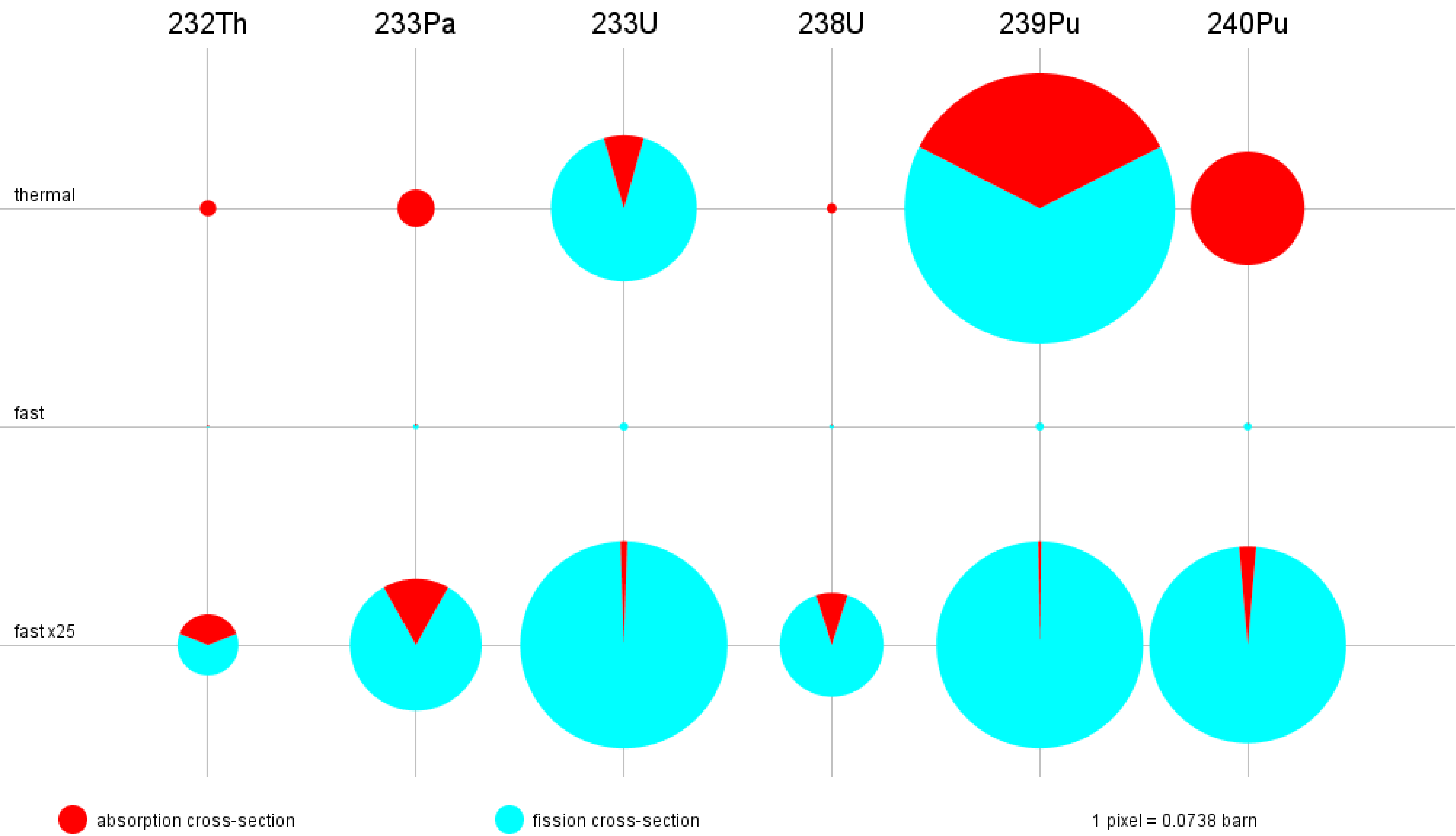


Th-233 has half life of 22 minutes. A neutron undergoes beta decay and turns into a proton. The decay releases an electron and an anti neutrino. The resulting element is Pa-233.

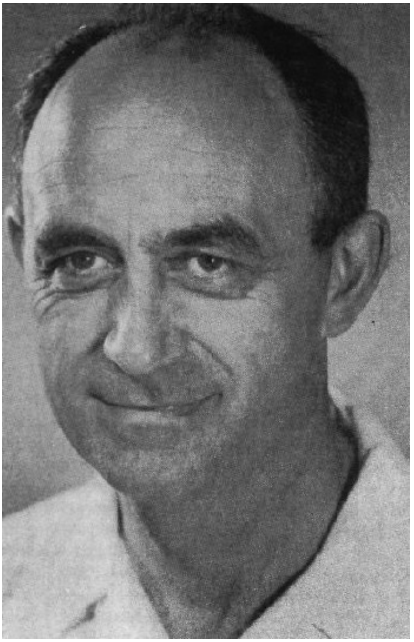
The neutrons that come from fission are moving very fast, and are not likely to cause fission or be absorbed. By striking carbon nuclei in graphite they give up almost all of that kinetic energy without being absorbed. The neutrons are then called "thermal neutrons" because they're at the same temperature as the rest of the salt mixture.

Th-232 absorbs a neutron and transmutes to Th-233.

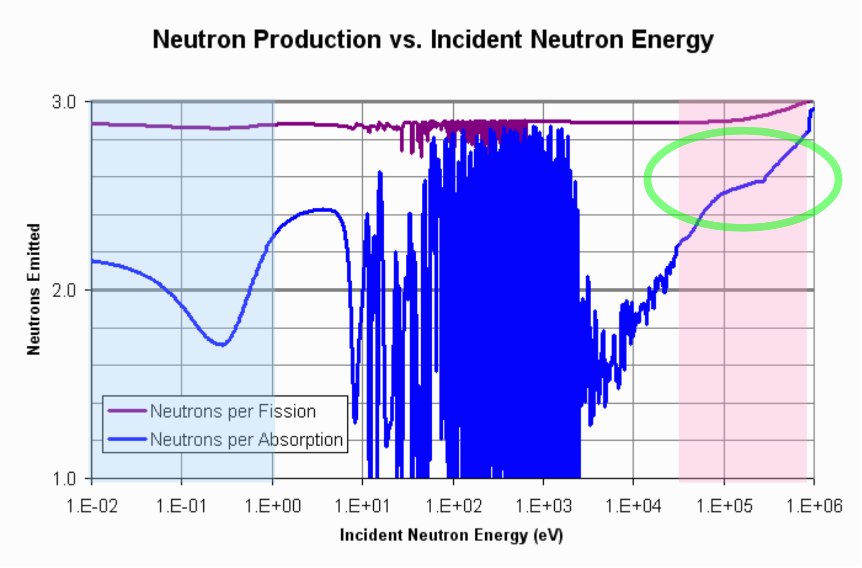
Relative Nuclide Cross-Sections



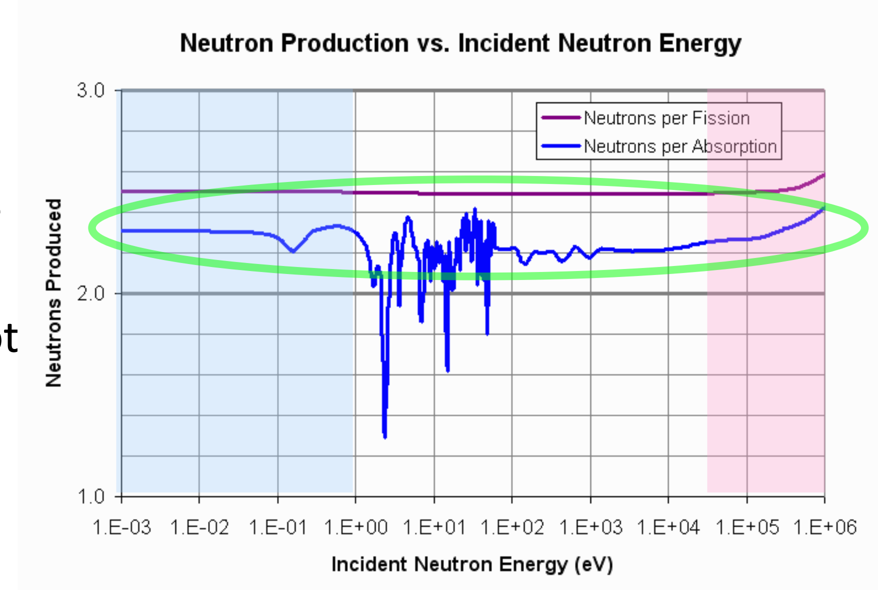
1944: A tale of two isotopes…



- 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).

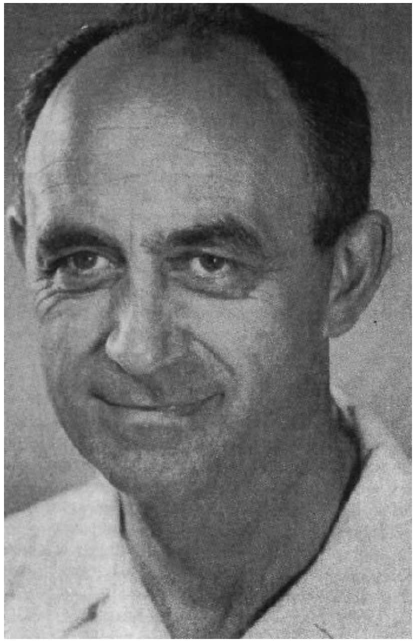


- Eugene Wigner argued for a thermal-breeder program using thorium as the fertile material and U-233 as the fissile material.
- Although large breeding gains were not possible, thermal spectrum breeding was possible, with advantages
- Wigner's protégé, Alvin Weinberg, followed Wigner's path at the Oak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

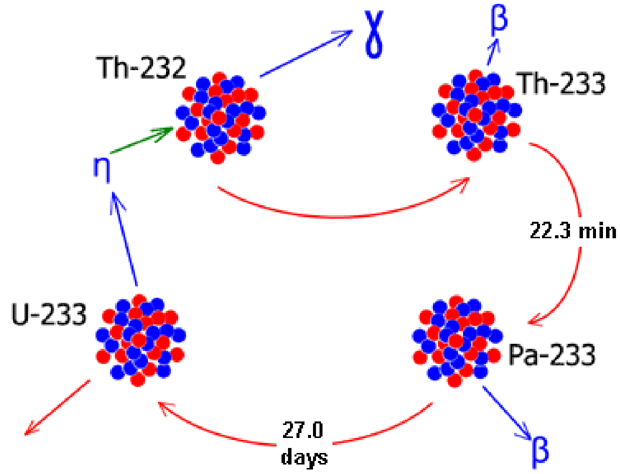


Details: **Fluid Fuel Reactors**, James A. Lane, H.G. MacPherson, & Frank Maslan (1958). http://www.energyfromthorium.com/pdf/

1944: A tale of two isotopes…



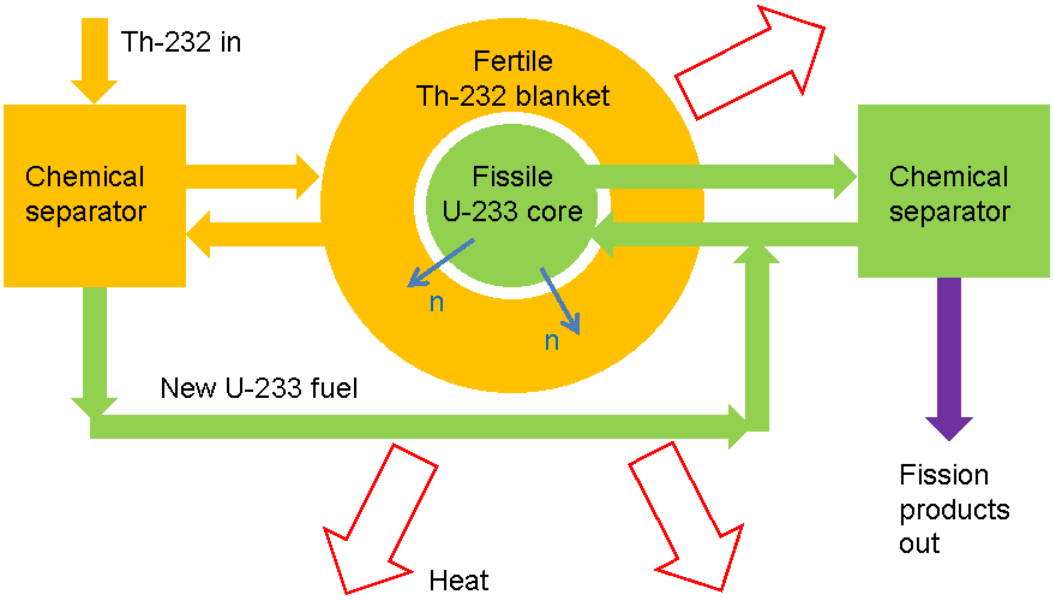
"But Eugene, how will you reprocess the thorium fuel effectively?"



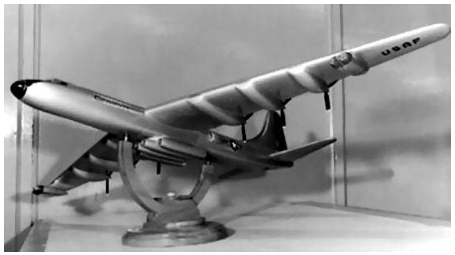
Thorium Fuel Cycle

"We'll build a fluid-fueled reactor, that's how…"

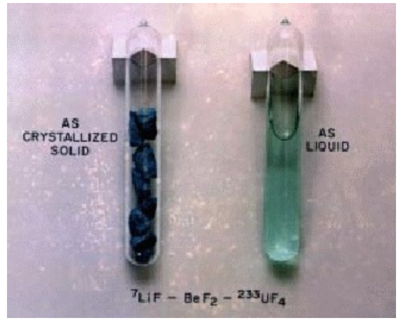
Schematic of the Liquid Fluoride Thorium Reactor (LFTR) by Kirk Sorensen,
http://www.energyfromthorium.com



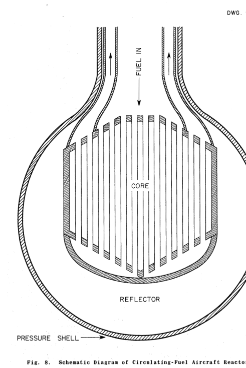
ORNL Aircraft Nuclear Reactor Progress (1949-1960)

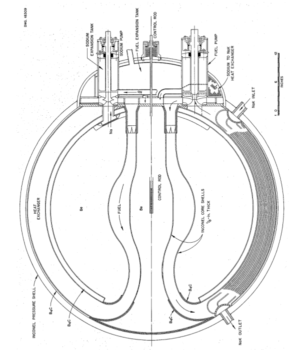


1949 – Nuclear Aircraft Concept formulated

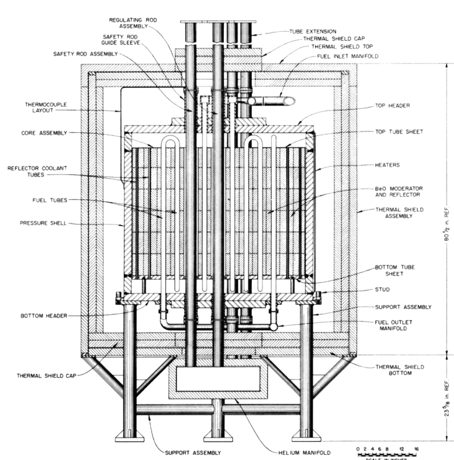


1951 – R.C. Briant proposed Liquid-Fluoride Reactor

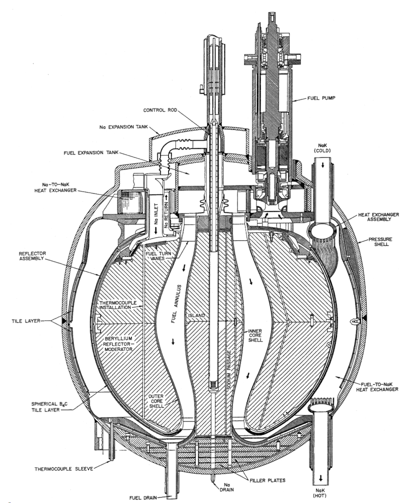




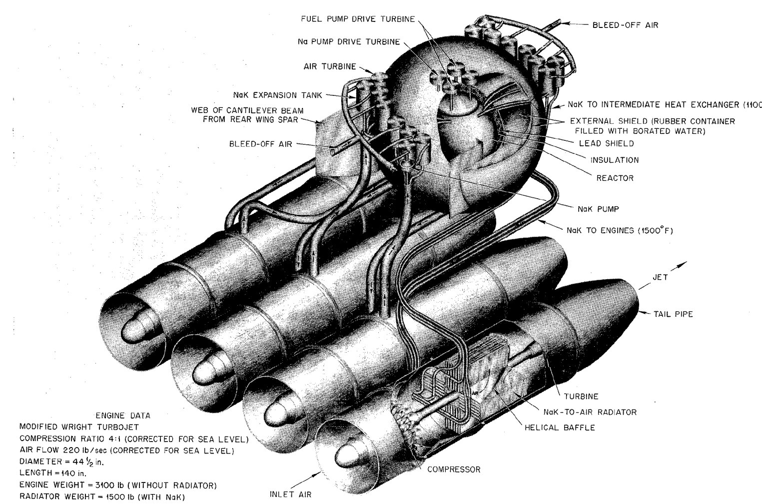
1952, 1953 – Early designs for aircraft fluoride reactor



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



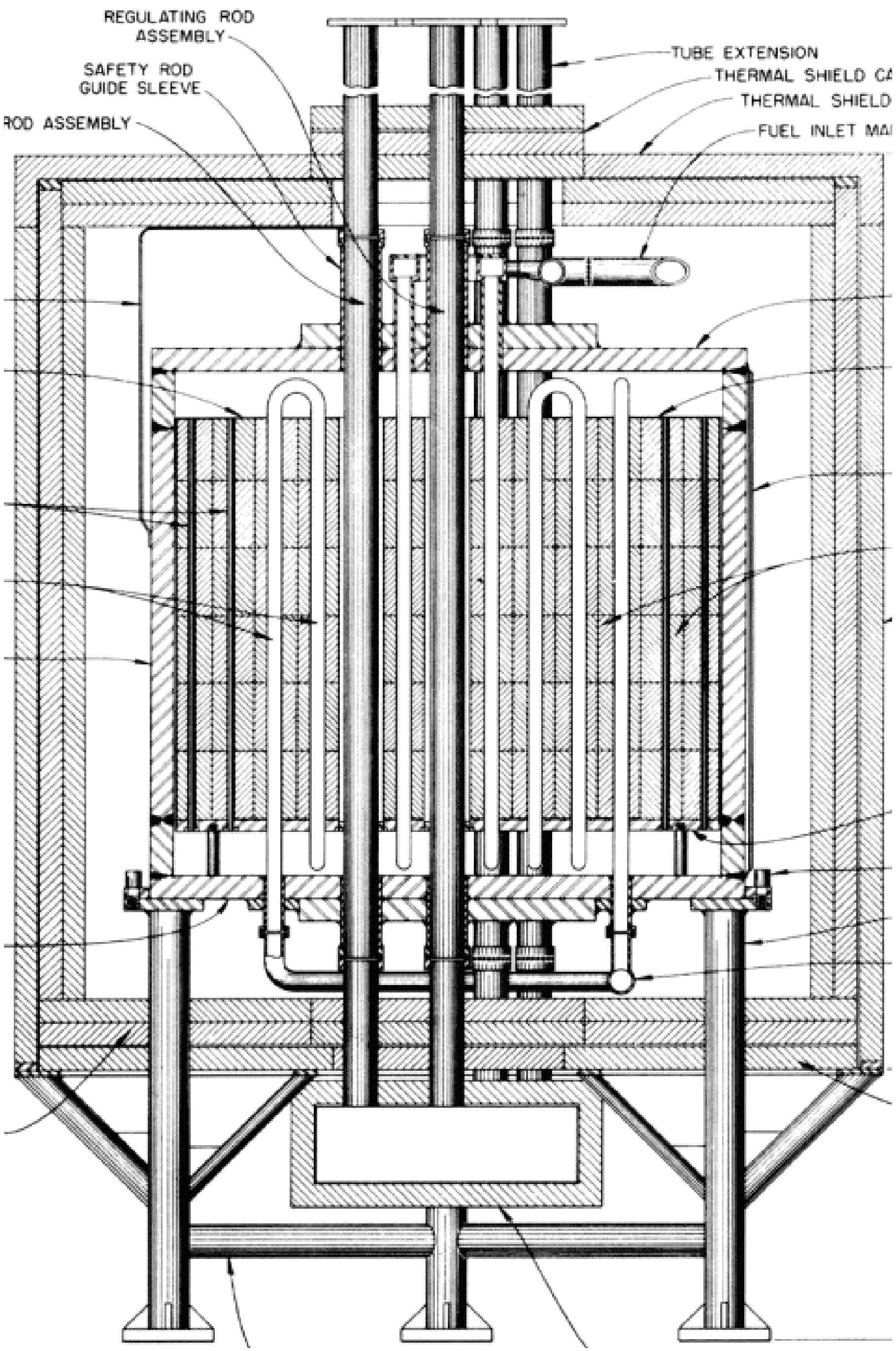
1955 – 60 MWt Aircraft Reactor Test (ART, "Fireball") proposed for aircraft reactor



1960 – Nuclear Aircraft Program canceled in favor of ICBMs

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

The Aircraft Reactor Experiment (ARE)

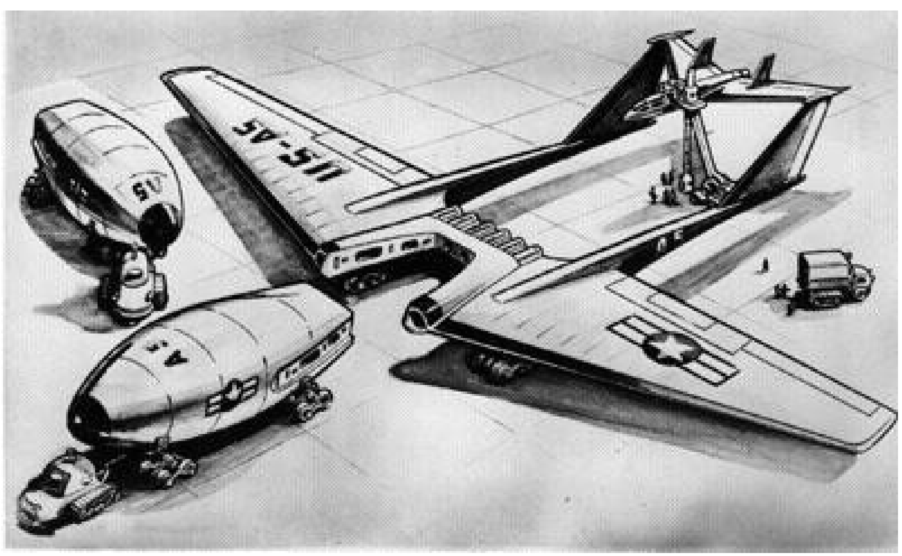


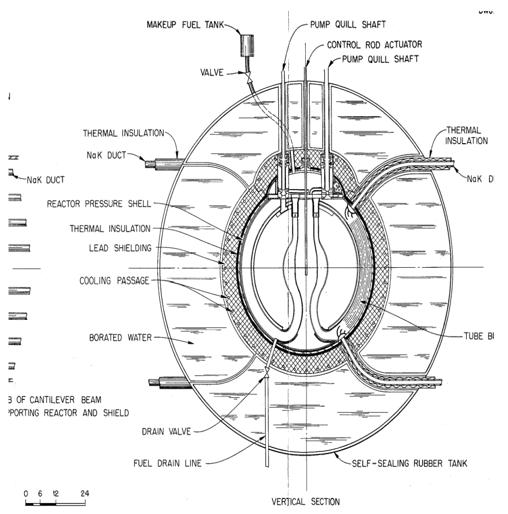
In order to test the liquid-fluoride reactor concept, a solid-core, sodium-cooled reactor was hastily converted into a proof-of-concept liquid-fluoride reactor.

The Aircraft Reactor Experiment ran for 100 hours at the highest temperatures ever achieved by a nuclear reactor (**1150 K**).

- Operated from 11/03/54 to 11/12/54
- Liquid-fluoride salt circulated through beryllium reflector in Inconel tubes
- $^{235}UF_4$ dissolved in $NaF\text{-}ZrF_4$
- Produced 2.5 MW of thermal power
- Gaseous fission products were removed naturally through pumping action
- Very stable operation due to high negative reactivity coefficient - self-controlling
- Demonstrated load-following operation without control rods

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)

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

ORNLs' MSRE: 8 MW(th)
Designed 1960 – 1964
Start in 1965, 5 years of successful operation

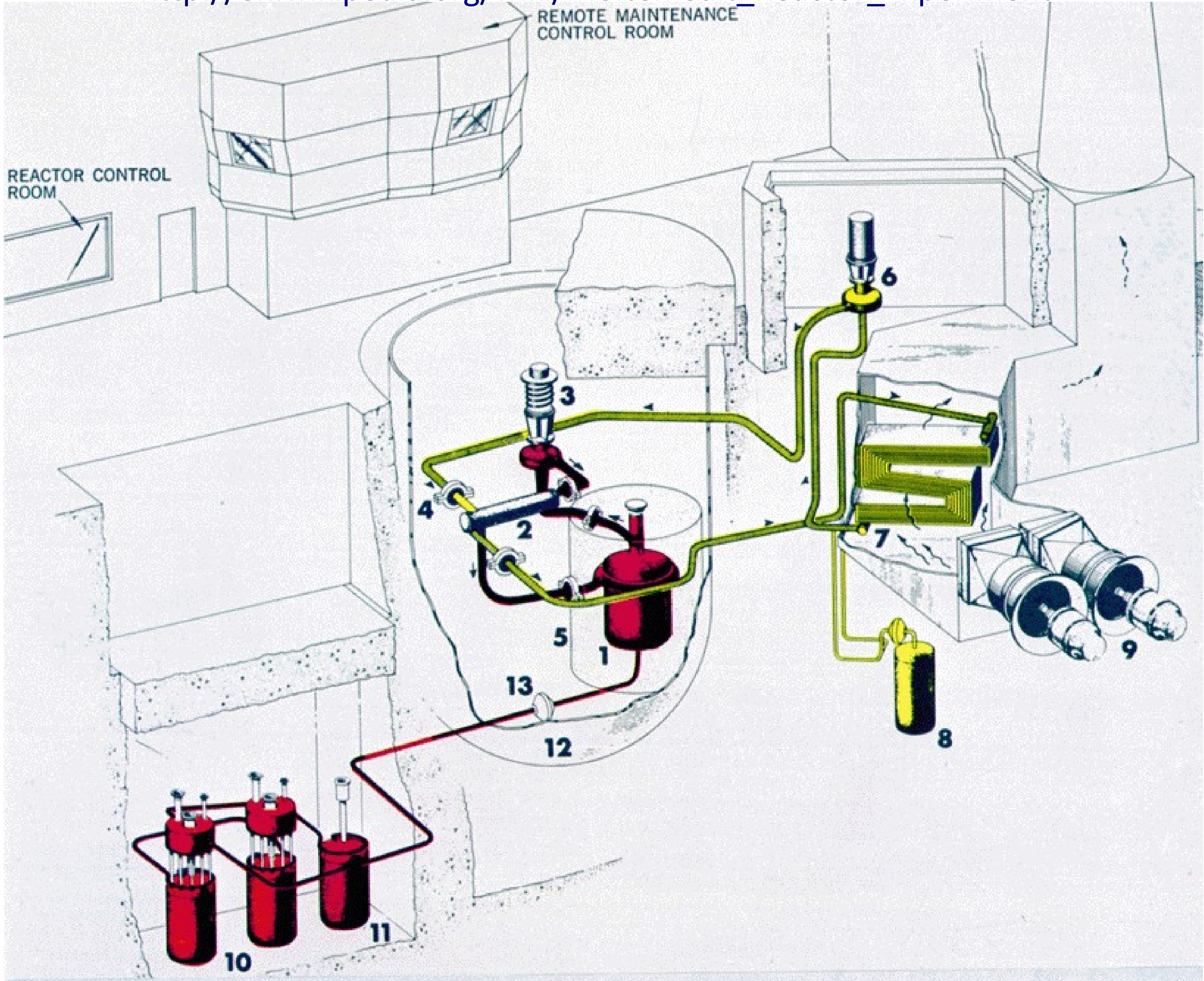
Developed and demonstrated on-line refueling, fluorination to remove uranium $UF_4+F_2 \rightarrow UF_6$, Vacuum distillation to clean the salt

Operated on all 3 fissile fuels
U233, U235, Pu239

Some issues with HaselloyN found and solved

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

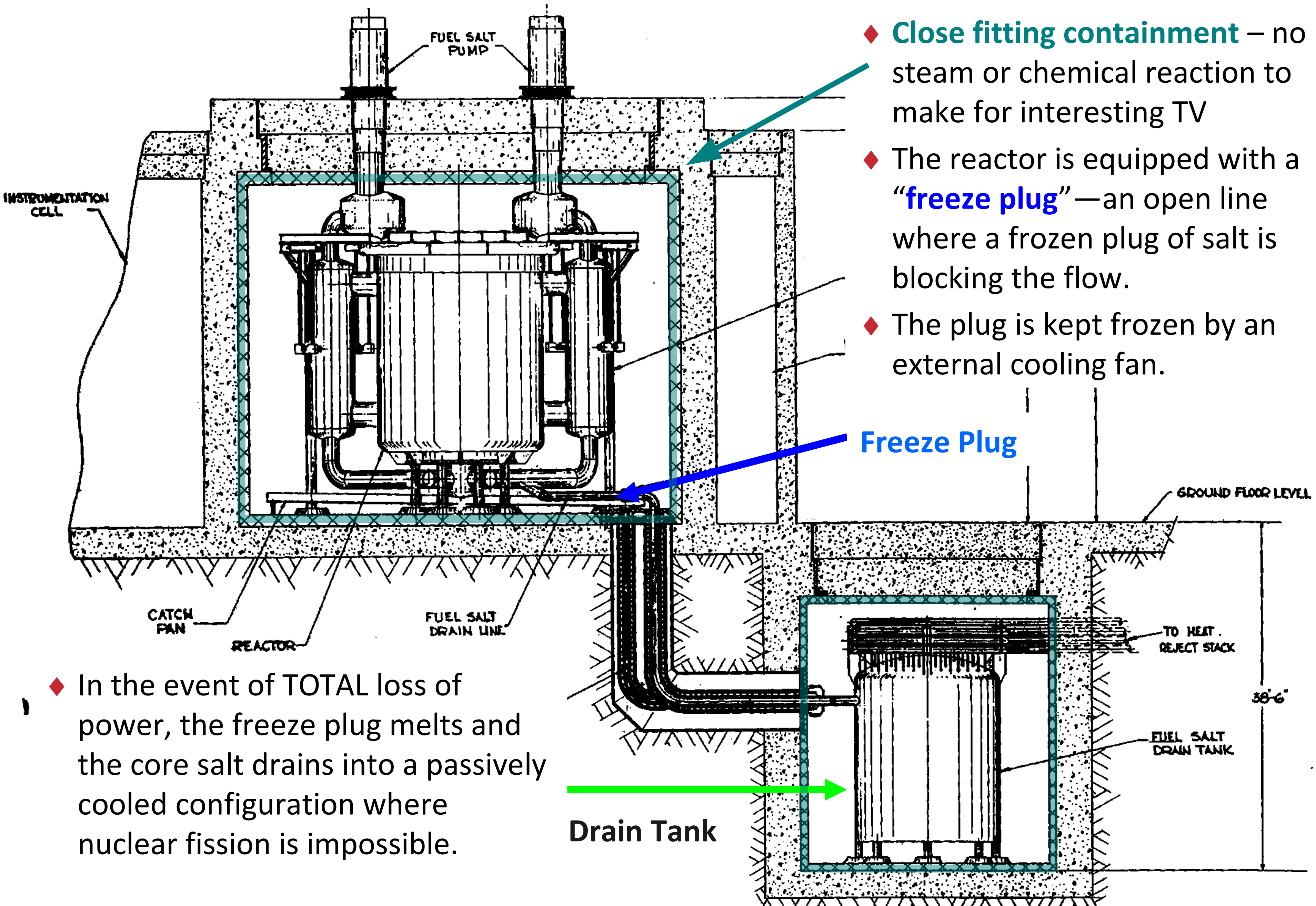
After Alvin Weinberg was removed from ORNL directorate, very little work done, almost no funding



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

The Molten Salt Reactor Adventure, H. G. MacPherson, NUCLEAR SCIENCE AND ENGINEERING: 90, 374-380 (1985)
http://home.earthlink.net/~bhoglund/mSR_Adventure.html

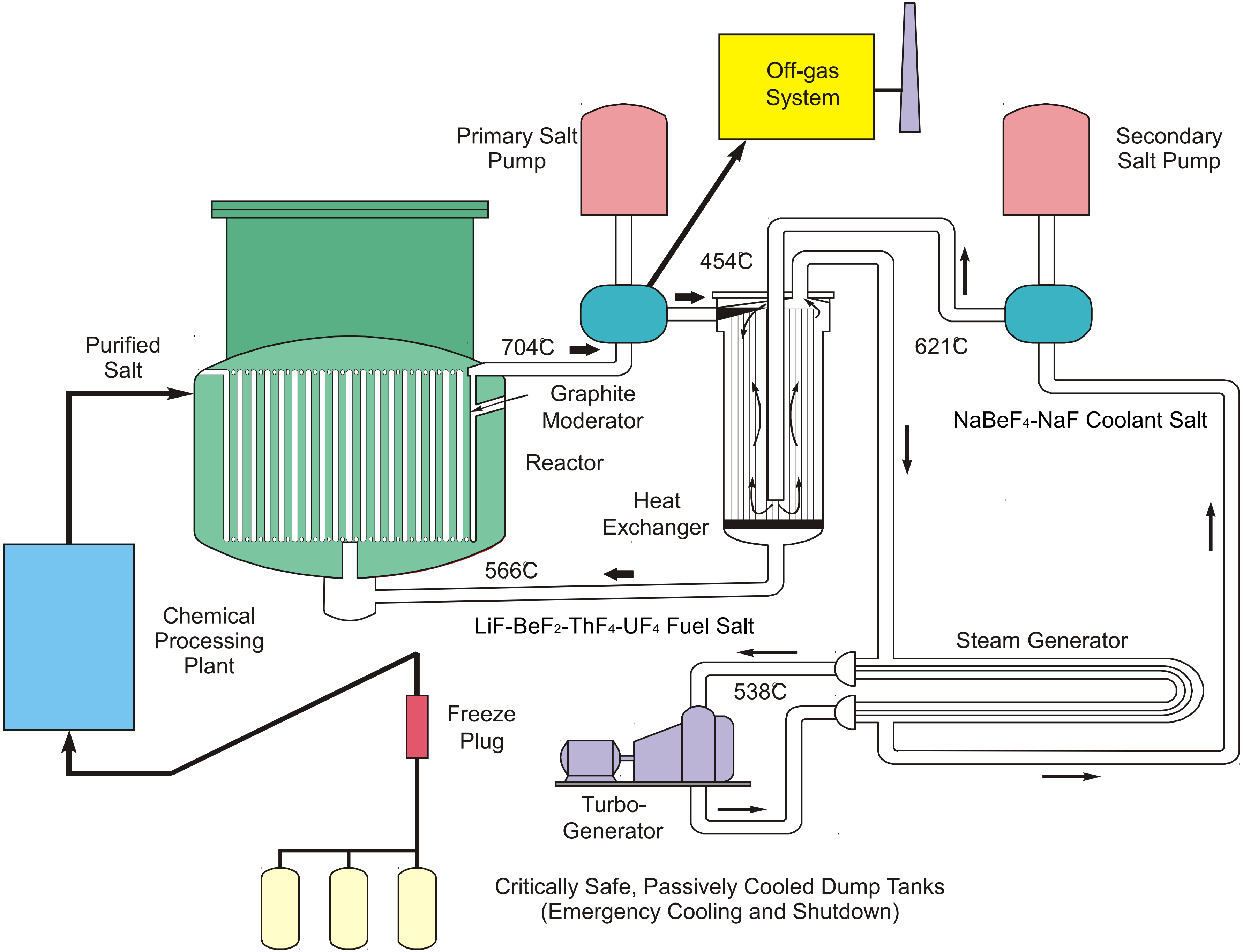
MSR is totally passively safe in case of an accident



- **Close fitting containment** – no steam or chemical reaction to make for interesting TV
- The reactor is equipped with a "**freeze plug**"—an open line where a frozen plug of salt is blocking the flow.
- The plug is kept frozen by an external cooling fan.

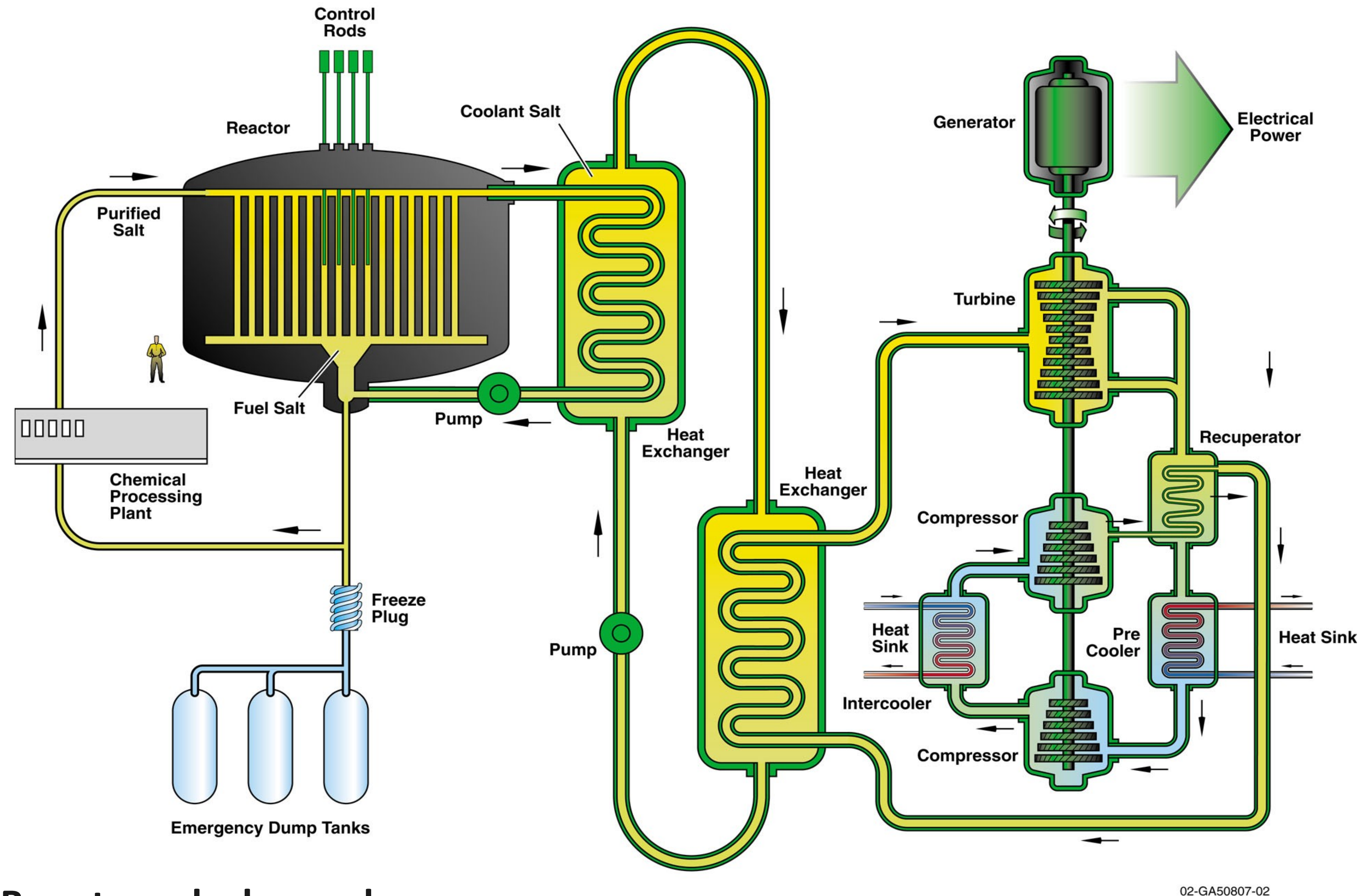
- In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission is impossible.

1972 Reference Molten-Salt Breeder Reactor Design



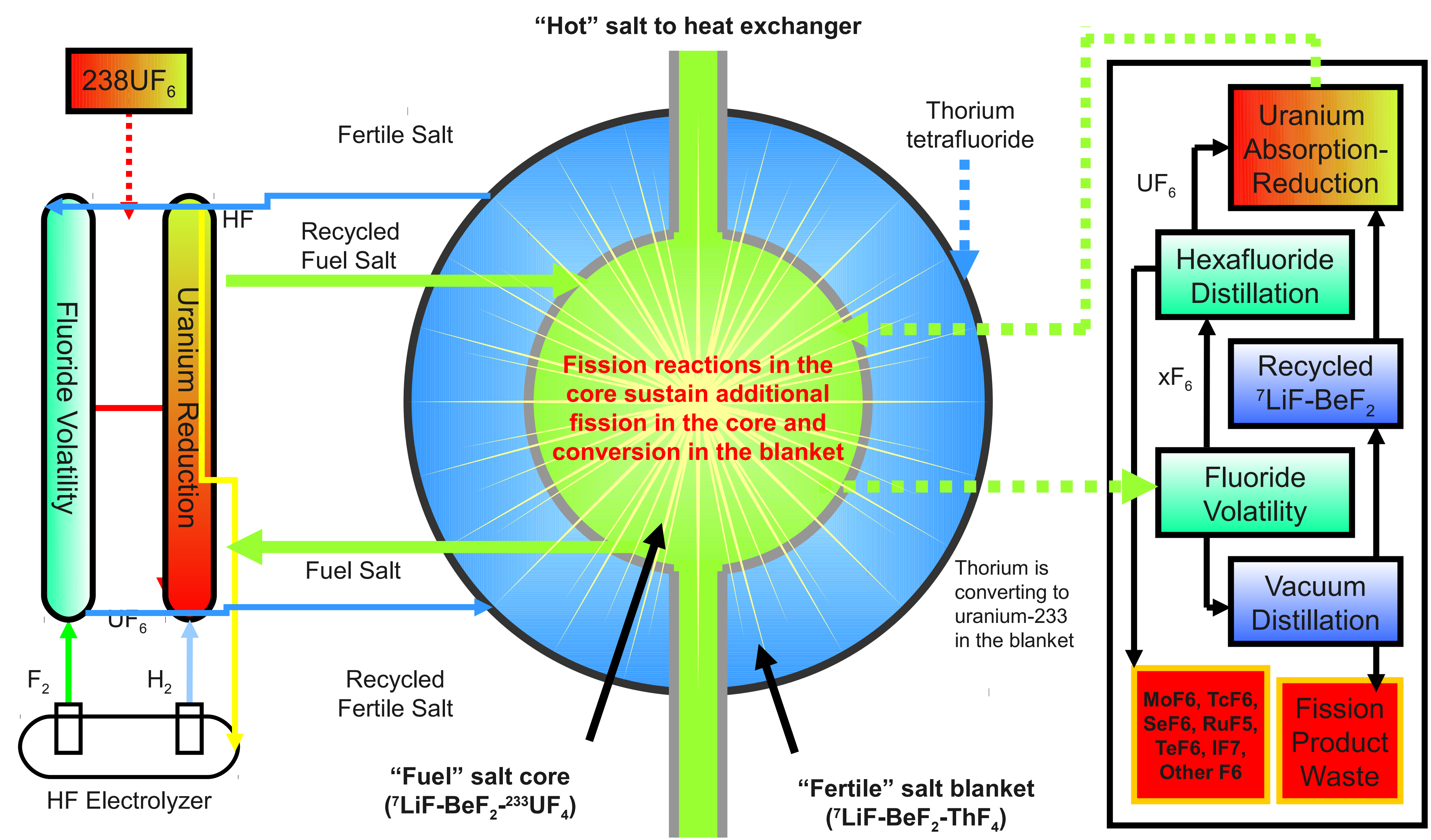
Ondřej Chvála, chvala@bnl.gov

A “Modern” Fluoride Reactor: Gen4 MSR



NB: not much changed …

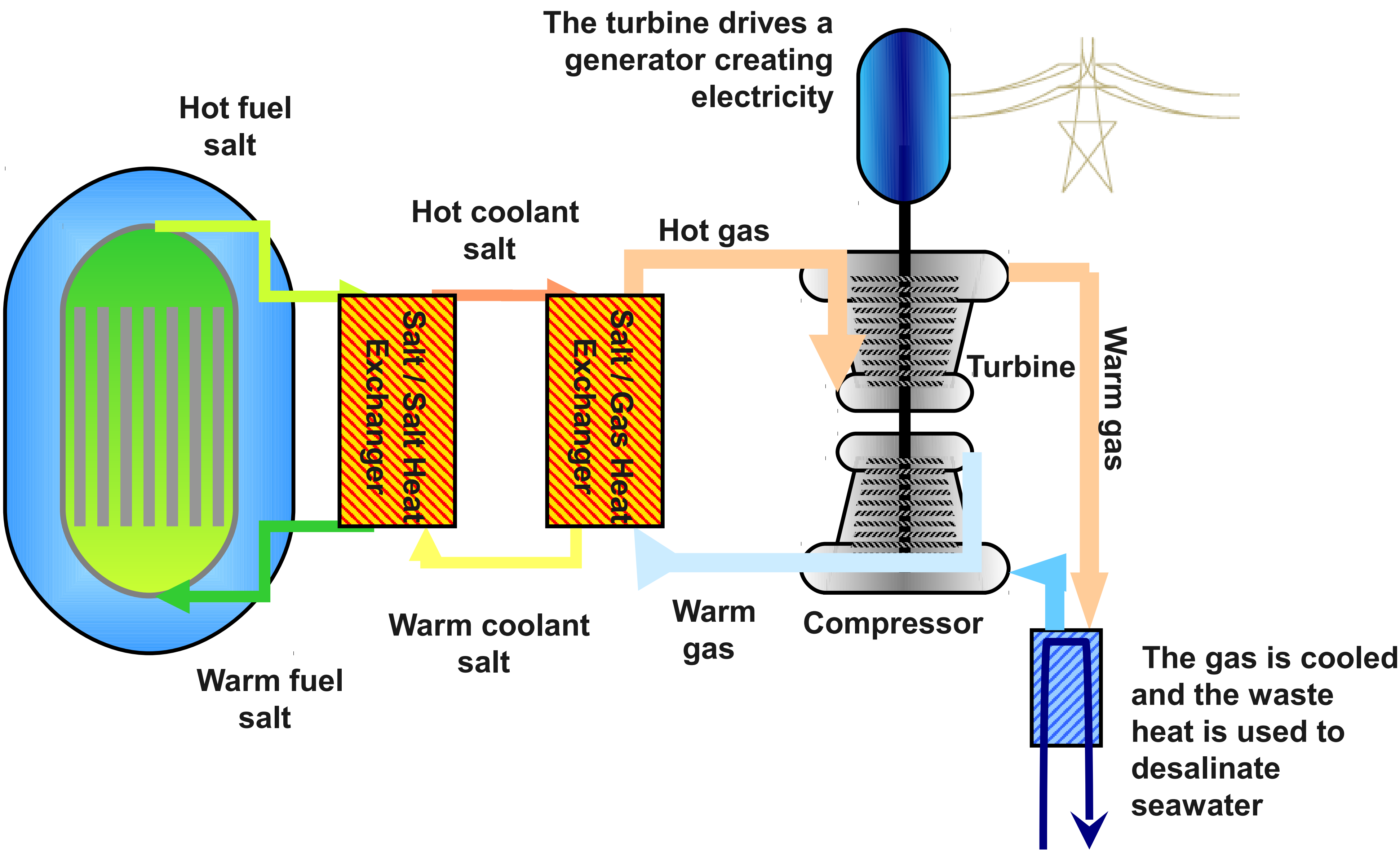
How does a fluoride reactor use thorium?



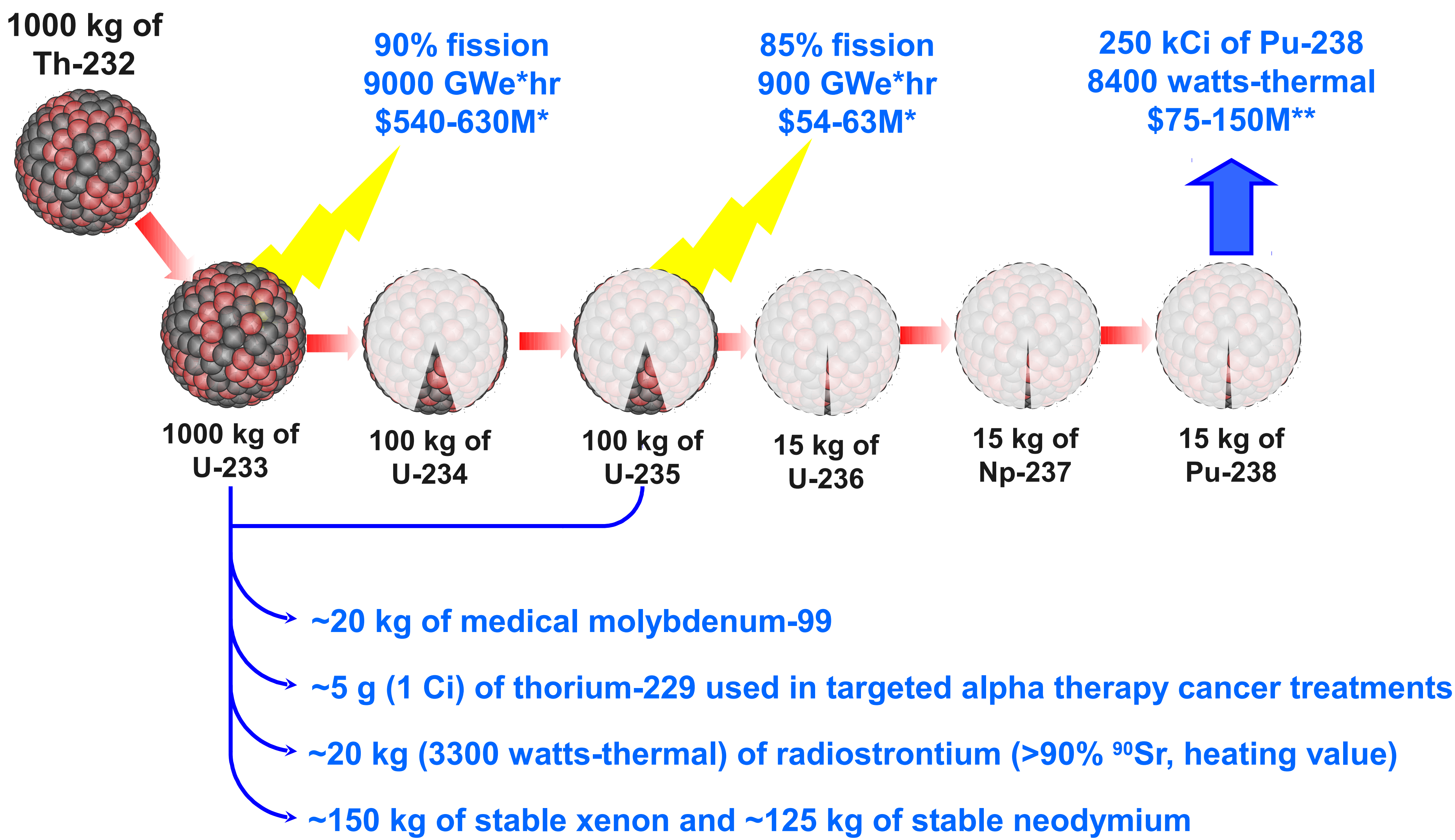
Internal continuous recycling of blanket salt

External "batch" processing of core salt, done on a schedule

How does a fluoride reactor make electricity?



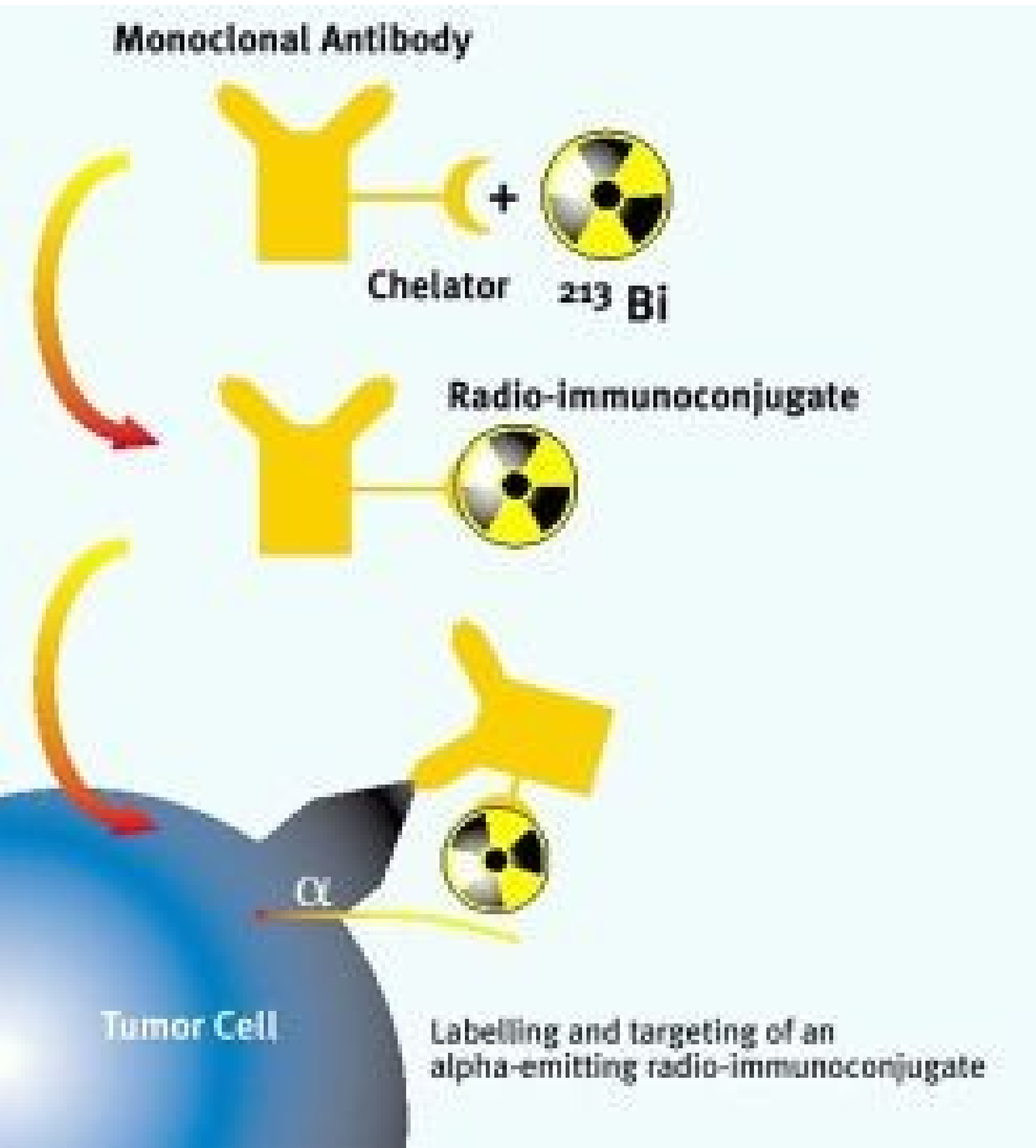
Electricity and Isotope Production from LFTR



Medical Radioisotopes from LFTR

Bismuth-213

(derived from U-233 decay)



Molybdenum-99

(derived from U-233 fission)

Why the recent interest?

Issues with fossil fuels are getting more and more troubling

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

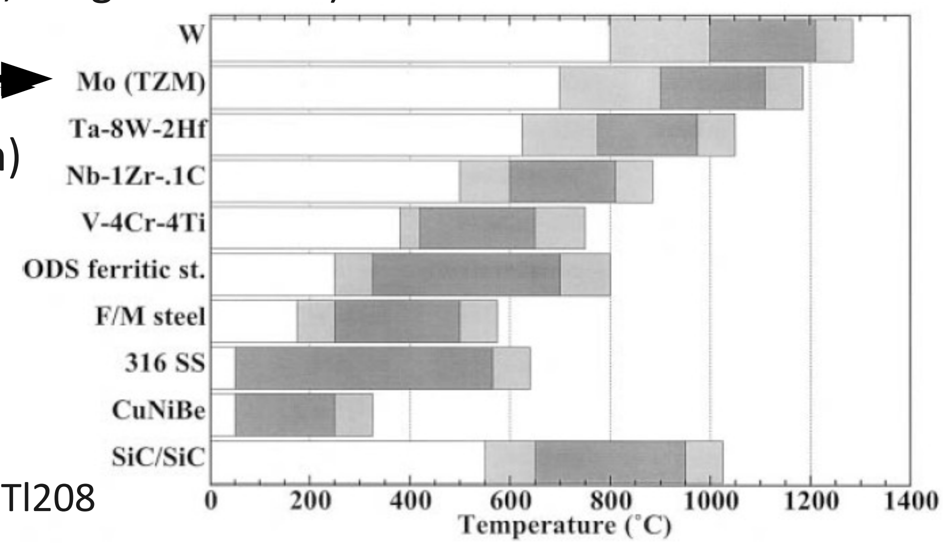
"The second nuclear age"

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



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

"Operating Temperature Windows for Fusion Reactor structural Materials"
Zinkle and Ghoniem, 2000

Proliferation resistance – U232 inevitably formed in Th cycle, Tl208 in its decay chain is a hard 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

General Benefits of a Molten Salt Design

Salts are chemically stable, have high boiling point, operate at low pressure
There are several salt choices, melting points 400-800C, boiling points 1400-1600C
→ High thermal efficiency (48%) with compact Brayton cycle engines, direct use of high temperature heat

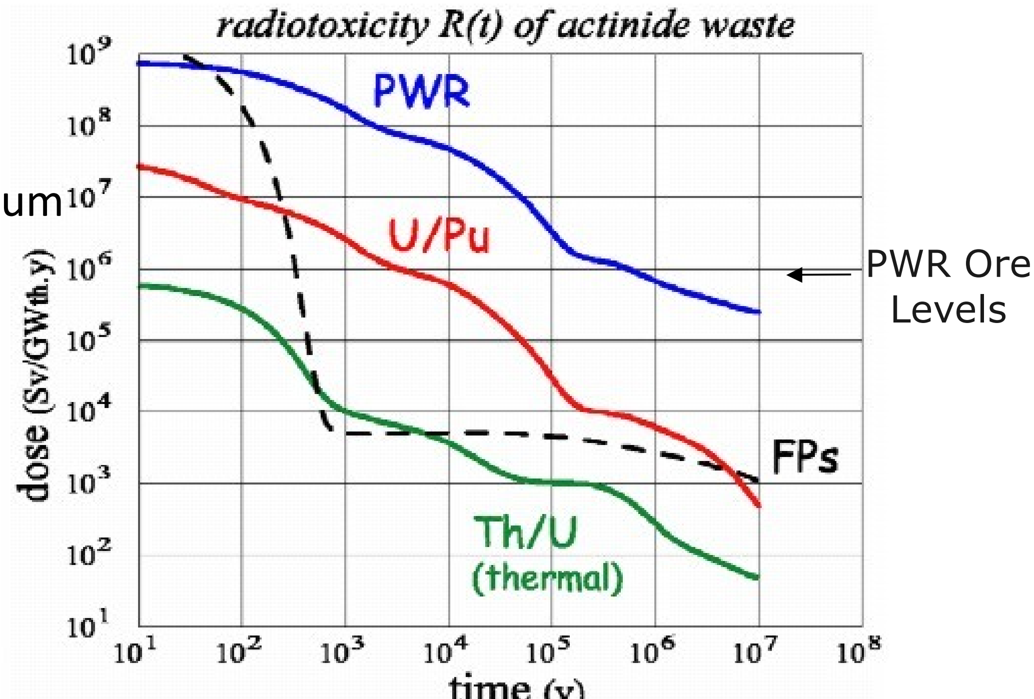
Volatile fission products continuously removed and stored, including Xenon.
Control rods or burnable poisons not required so very little excess reactivity
→ Low fissile inventory, fast doubling time achievable even with small breeding gain

Fuel salt at the lowest pressure of the circuit, the opposite of a LWR
Freeze plug melts upon fuel overheating to drain to critically safe, passively cooled dump tanks → Passive safety

Ideal for LWR **TRU waste destruction**
Ability to use **closed thorium cycle** in thermal spectrum
- UF_4+F_2 → UF_6(gaseous)
- Only consume 800 kg thorium per GW/year
- Transuranic waste production extremely low
- Much lower long term waste toxicity

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

(plot taken from David LeBlanc's talk)



Edward Teller promoted MSR to the last month of life

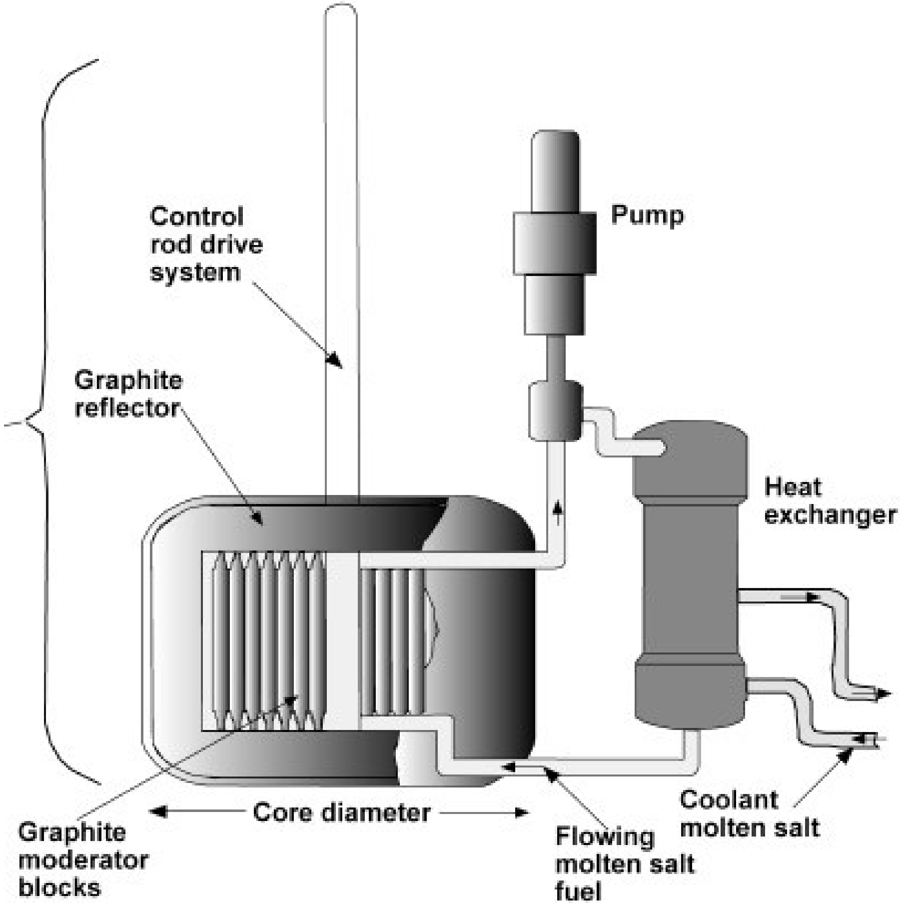
THORIUM-FUELED UNDERGROUND POWER PLANT BASED ON MOLTEN SALT TECHNOLOGY

FISSION REACTORS

TECHNICAL NOTE

RALPH W. MOIR* and EDWARD TELLER†
Lawrence Livermore National Laboratory, P.O. Box 808, L-637
Livermore, California 94551

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



Czech Republic – NRI Řež

- Worked on molten salt chemistry since the 1960s, leading members of GenIV forum, cooperating with ORNL research efforts

- Supported by Czech spent nuclear fuel repository agency and Ministry for Industry and Trade

- Experimental and theoretical work on both fluoride chemistry and nuclear reactor design including:
  - fluoridation line FERDA
  - molten salt electro-refining experiments
  - molten salt test loop
  - two flexible research reactors
  - reactor physics experiment "EROS" to test molten salt fuels
  - recent paper on a MSR concept with 2.6 years of doubling time

  http://www.energyfromthorium.com/forum/viewtopic.php?p=22452#p22452

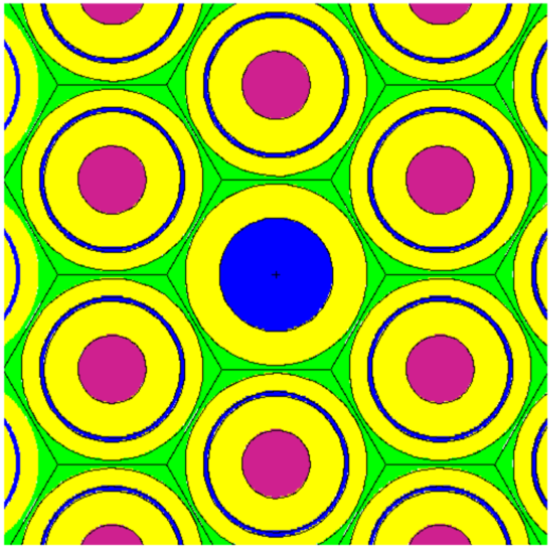


Fig. 1. Horizontal cross-section of the reactor core. Graphite (yellow), fuel salt (purple), fertile salt (blue) and helium (green).

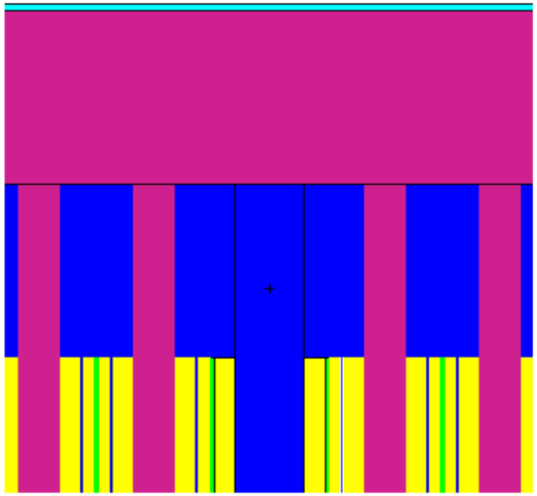
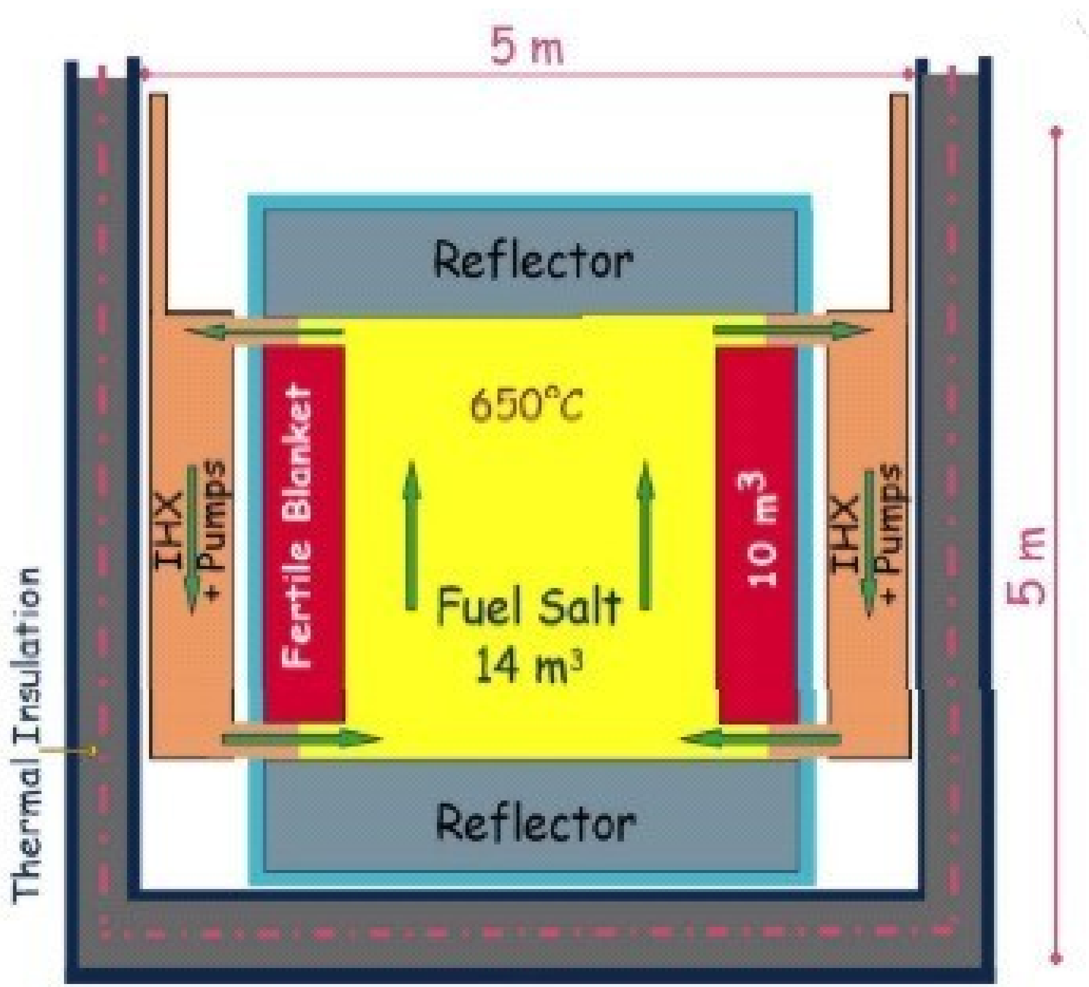


Fig. 3. Top vertical plenum

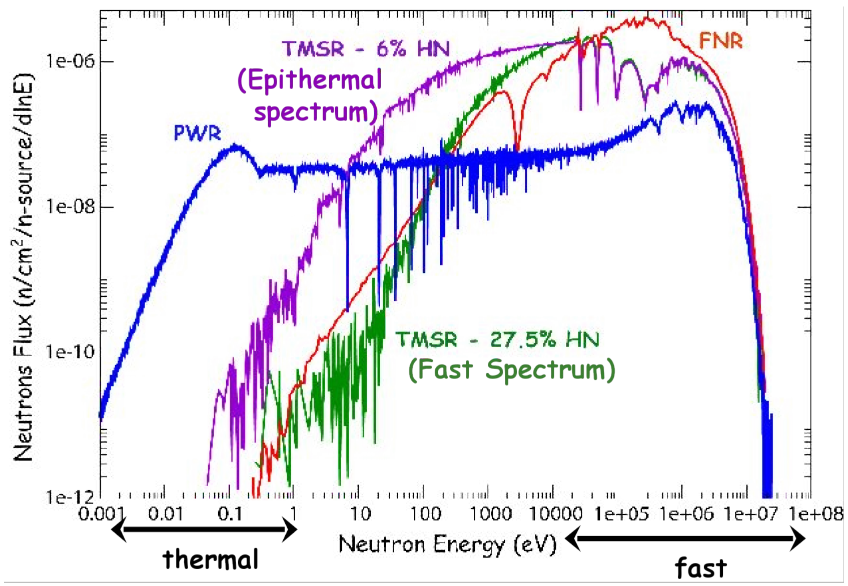
- Škoda JS developed a MoNiCr alloy - improved HastalloyN for MSR components

More information: http://www.energyfromthorium.com/forum/viewtopic.php?f=13&t=1747

French TMSR: Thorium Molten Salt Reactor



Flexibility in neutron spectrum



Schedule

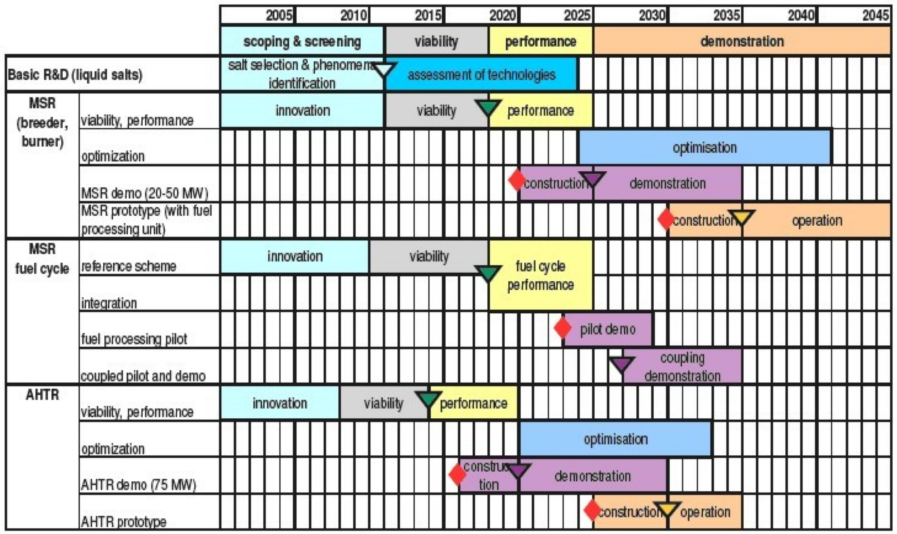
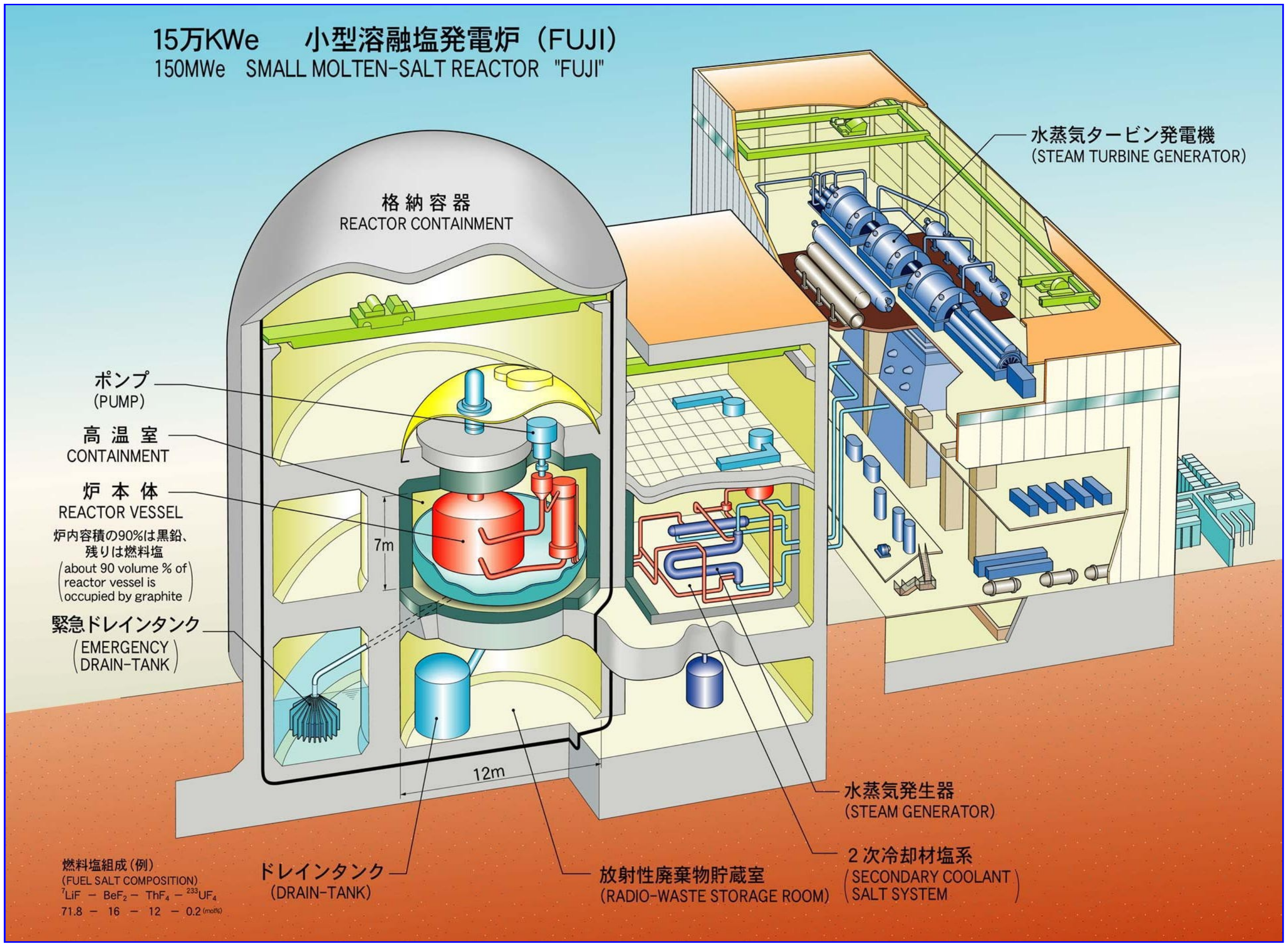


FIG. 1.3 – "Master Plan" du système Réacteurs à Sels Fondus dans le forum International Generation IV [14]

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

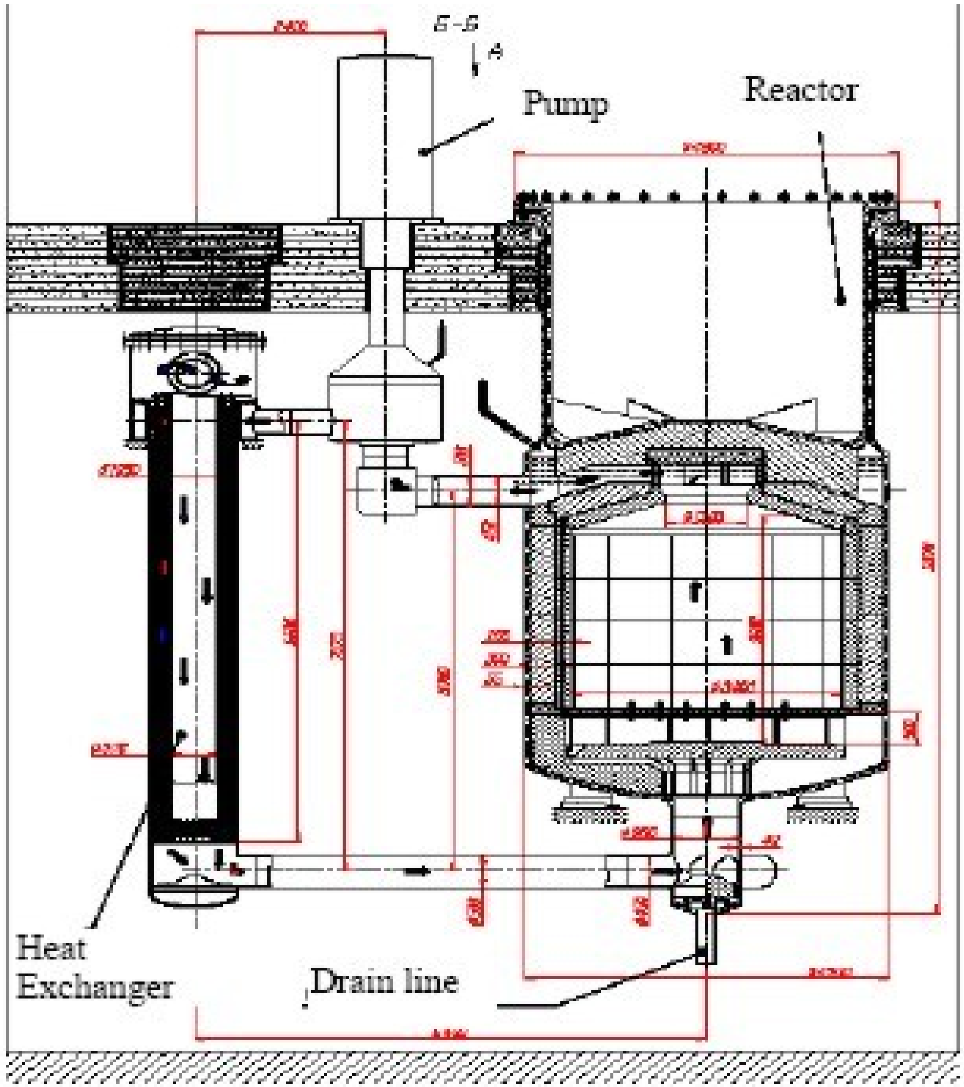
Japan - IThEMS

Consortium of Toyta, Totshiba, Hitashi presented plants to develop aThorium MSR.
First a 7MWe miniFUJI, then 150 MWe FUJI reactor



http://en.wikipedia.org/wiki/Fuji_Molten_Salt_Reactor
http://nextbigfuture.com/2010/10/partnerships-toward-minifuji-thorium.html

Russian MOlten Salt Actinide Recycler and Transmuter MOSART



Developed by Kurchatov Institute

Single fluid in a tank, fast spectrum, no breeding, but TRU waste disposal (actinide burner)

From: http://www.torium.se/res/Documents/7548.pdf
See also: http://nuclear.inl.gov/deliverables/docs/msr_deliverable_doe-global_07_paper.pdf

Fluoride salt High temperature Reactor (FHR)

a.k.a Advanced High Temperature Reactor (AHTR)

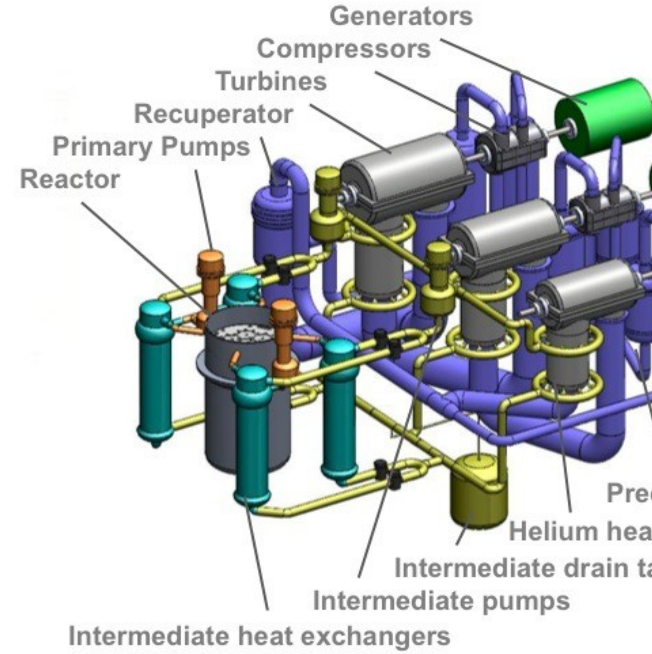
Supported by DoE, under development at ORNL (David Holcomb, Sherrel Greene, Jess Gehin) and at UC Berkeley (prof. Per Peterson's group)

Coated particle fuel manufactured at ORNL, tests in progress at INL

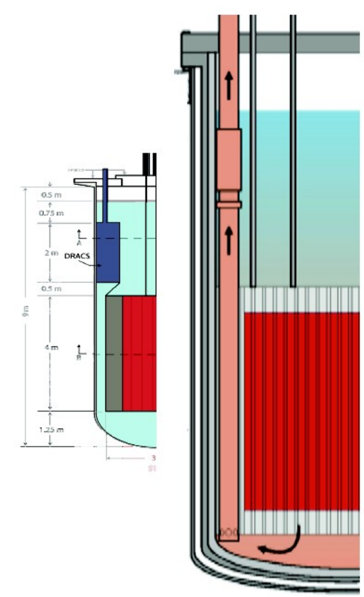
3 designs under development:
1250 MWe AHTR, 410 MWe PB-AHTR, 50 MWe SmAHTR
and a small test reactor, 16MWth 16-FHR

Coated particle fuel can operate as
- once-through cycle
- modified once-through (limited reprocessing)
- full reprocessing at central facility

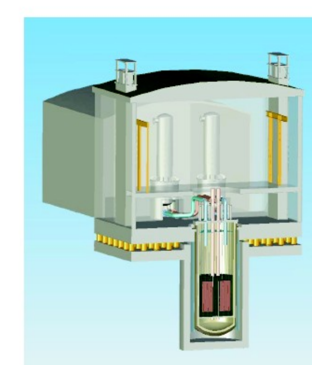
PB-AHTR



SmAHTR

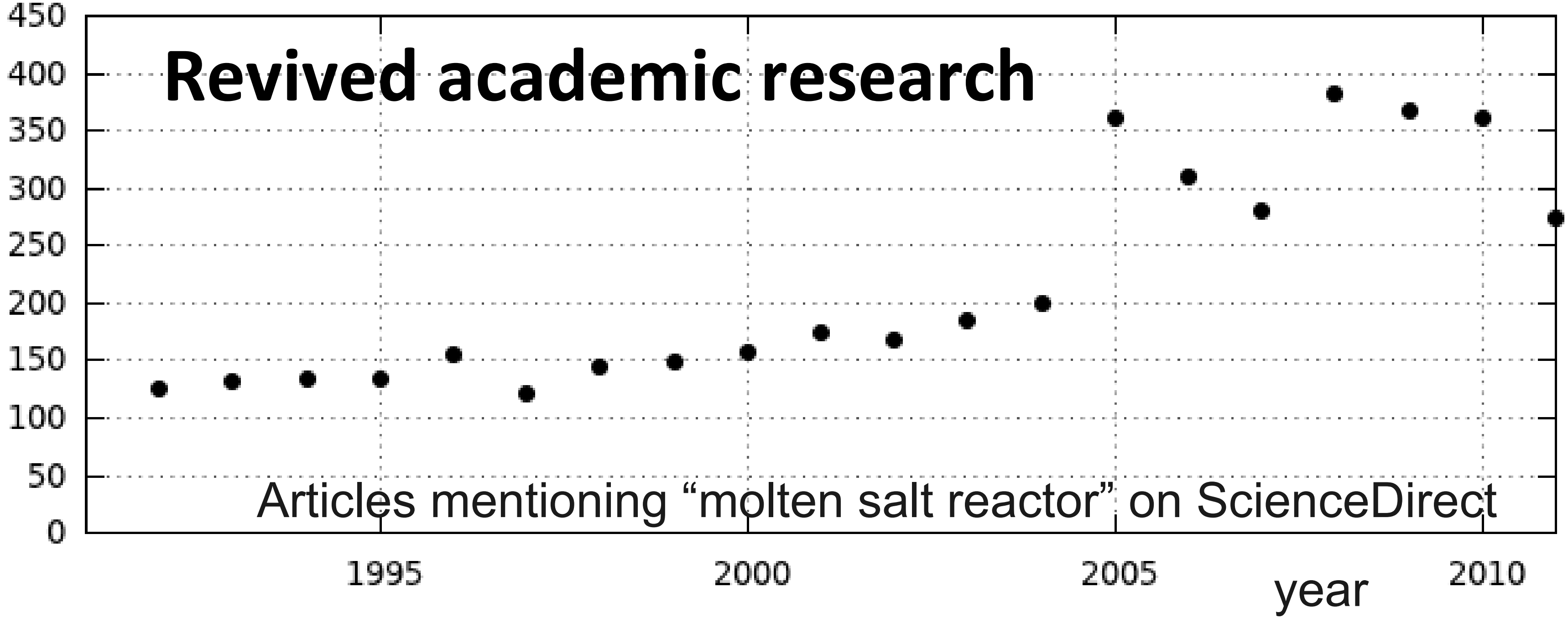


AHTR



Homepage: http://www.nuc.berkeley.edu/pb-ahtr/
Discussion: http://www.energyfromthorium.com/forum/viewtopic.php?f=58&t=1504

Revived academic research



Recent moves towards commercialization

- Flibe Energy based in Huntsville, AL, USA is developing thermal U/Th breeder aimed at US army application, in particular base power, aiming for first criticality in July 2015 (50 years anniversary of MSRE startup)
- Investment consortium is investigating 3 different MSR concepts (thermal breeder, DMSR, fast breeder) to power diesel dependent industries in developing world
- Chinese announced development of Thorium MSR, by Jiang Mianheng (vice president of Chinese Acdemy of Sciences, son of Jiang Zemin)

  http://energyfromthorium.com/2011/01/30/china-initiates-tmsr/

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)

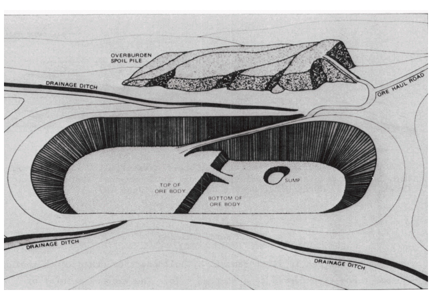
Generates ~600,000 t of waste rock

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

Generates 130,000 t of mill tailings

Generates 170 t of solid waste and 1600 m^3 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

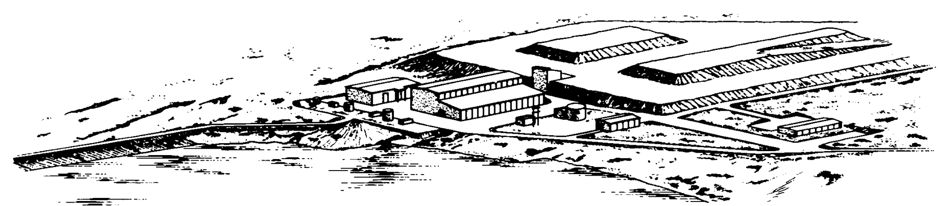


Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from

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.
  - Today thorium is a waste from rare earth mining
    - a liability thus better than for free
- 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

ORNL-DWG 78-12804

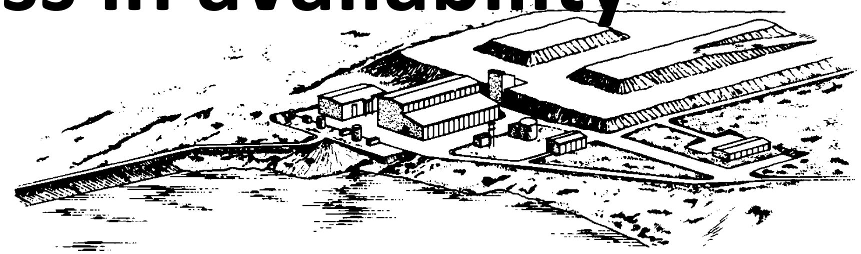
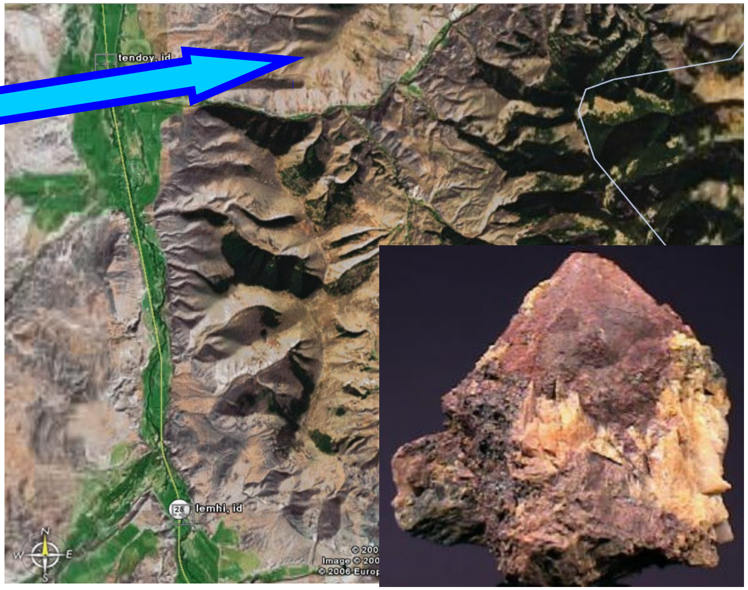
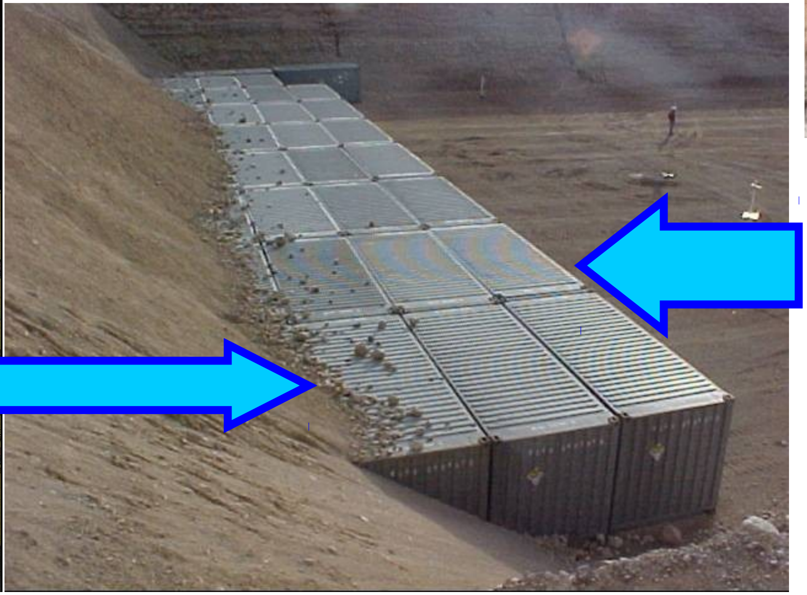


Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from U.S. Nuclear Regulatory Commission, Final Environmental Statement Bear Creek Project, NUREG-0129, Docket No. 40-8452, June 1977.)





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!

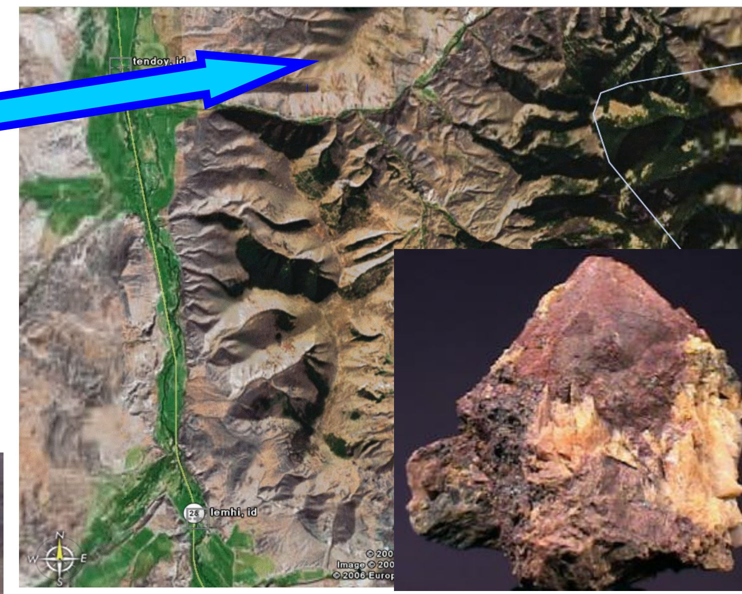
Ondřej Chvála, chvala@bnl.gov

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.
  - Today thorium is a waste from rare earth mining
    - a liability thus better than for free
- 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

ORNL-DWG 78-12804

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 ~200 Mev/232 amu and complete consumption. This energy can be converted to electricity at ~50% efficiency using a multiple-reheat helium gas turbine; or to hydrogen at ~50% efficiency using a thermo-chemical process such as the sulfur-iodine process.**

2007 World Energy Consumption

5.3 billion tonnes of **coal** (128 quads)

31.1 billion barrels of **oil** (180 quads)

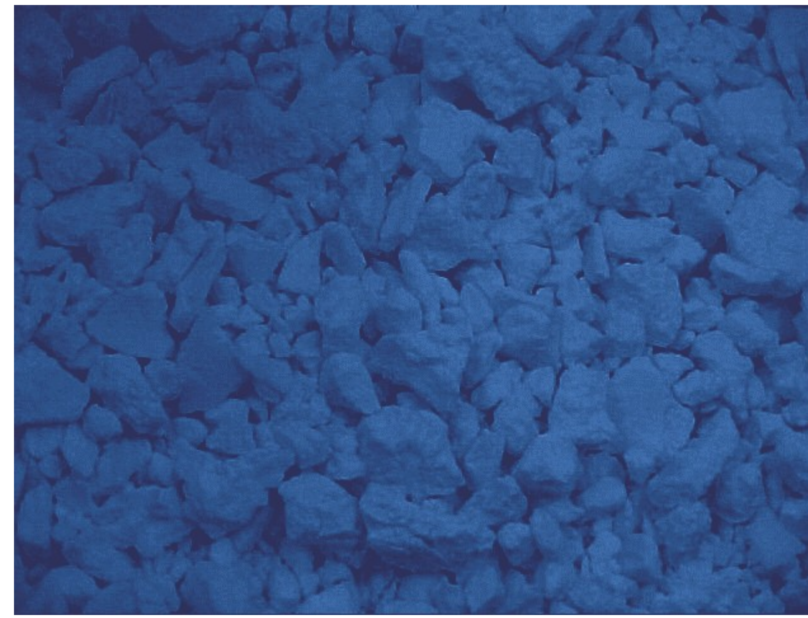
2.92 trillion m^3 of **natural gas** (105 quads)

65,000 tonnes of **uranium** (24 quads)

29 quads of **hydro** electricity

The Future:

Energy from Thorium



6,600 tonnes of **thorium**

(500 quads)

[Side product of a medium sized rare earth element mine]

Conclusions

Affordable energy necessary for progress of humanity

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

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

Solar renewables, energy storage – invest into R&D 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 alleviates many of these issues

Molten salt reactors are demonstrated technology which can solve all these issues, and provide additional benefits (sorted useful fission products, medical isotopes, Pu238)
Check on the web: http://energyfromthorium.com/

"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

Why wasn’t this done? No Plutonium!

Alvin Weinberg:

“Why didn't the molten-salt system, so elegant and so well thought-out, prevail? I've already given the political reason: that the plutonium fast breeder arrived first and was therefore able to consolidate its political position within the AEC. But there was another, more technical reason. [Fluoride reactor] technology is entirely different from the technology of any other reactor. To the inexperienced, [fluoride] technology is daunting…

“I found myself increasingly at odds with the reactor division of the AEC. The director at the time was Milton Shaw. Milt was cut very much from the Rickover cloth: he had a singleness of purpose and was prepared to bend rules and regulations in achievement of his goal. At the time he became director, the AEC had made the liquid-metal fast breeder (LMFBR) the primary goal of its reactor program. Milt tackled the LMFBR project with Rickoverian dedication: woe unto any who stood in his way. This caused problems for me since I was still espousing the molten-salt breeder.”

“Mac” MacPherson:

The political and technical support for the program in the United States was too thin geographically…only at ORNL was the technology really understood and appreciated. The thorium-fueled fluoride reactor program was in competition with the plutonium fast breeder program, which got an early start and had copious government development funds being spent in many parts of the United States.

Alvin Weinberg:

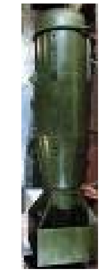
“It was a successful technology that was dropped because it was too different from the main lines of reactor development… I hope that in a second nuclear era, the [fluoride-reactor] technology will be resurrected.”

Could weapons be made from the fissile material?

Natural uranium

Isotope separation plant (Y-12)

Uranium-235 ("highly enriched uranium")



Hiroshima, 8/6/1945

Depleted uranium

Isotope Production Reactor (Hanford)

Pu separation from exposed U (PUREX)

Trinity, 7/16/1945 Nagasaki, 8/9/1945

Thorium? → Isotope Production Reactor → uranium separation from exposed thorium →

PROBLEM: U-233 is contaminated with U-232, whose decay chain emits HARD gamma rays that make fabrication, utilization and deployment of weapons VERY difficult and impractical relative to other options. Thorium was not pursued.

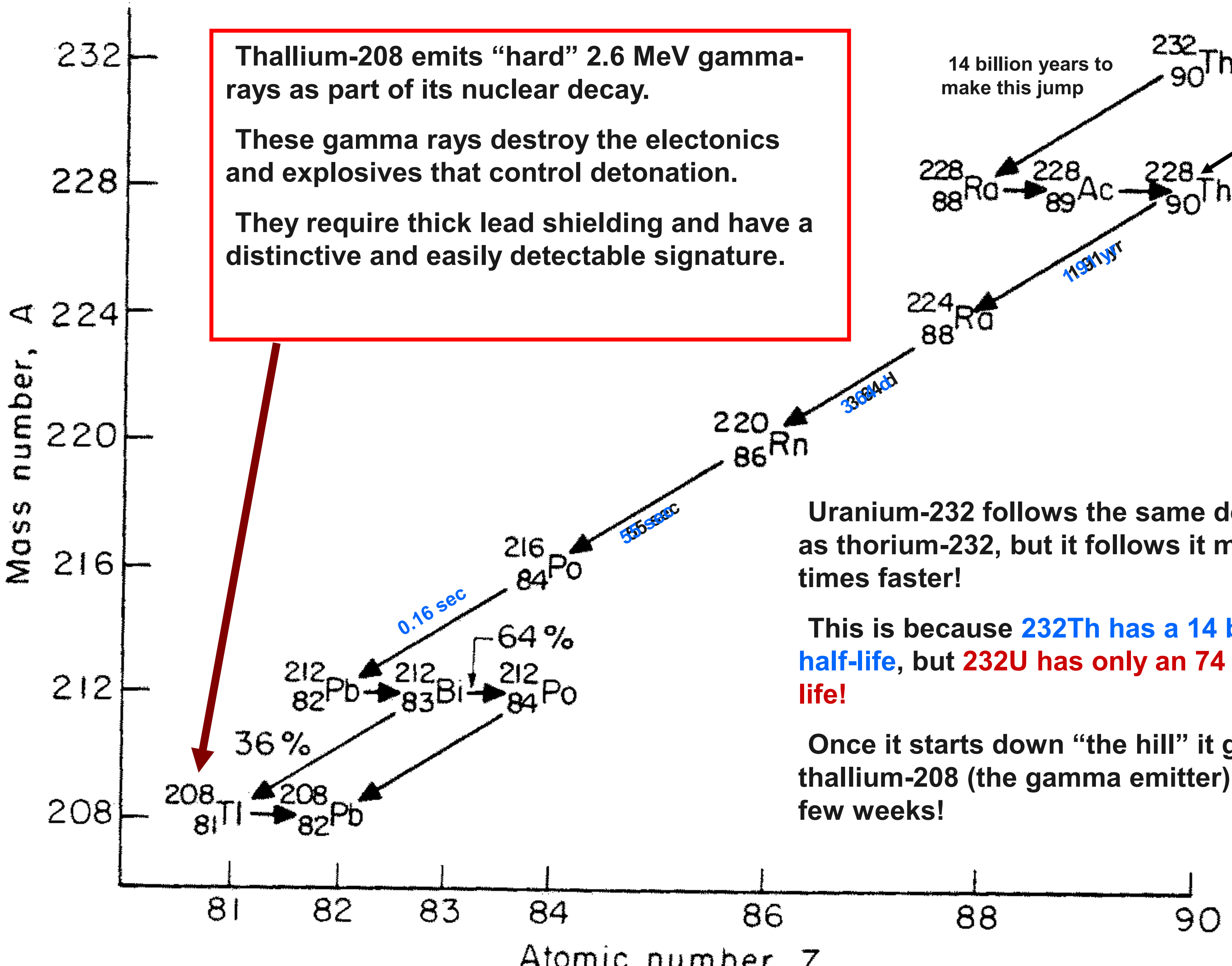
Ondřej Chvála, chvala@bnl.gov

U-232 decays into Tl-208, a HARD gamma emitter

Thallium-208 emits "hard" 2.6 MeV gamma-rays as part of its nuclear decay.

These gamma rays destroy the electonics and explosives that control detonation.

They require thick lead shielding and have a distinctive and easily detectable signature.



Uranium-232 follows the same decay chain as thorium-232, but it follows it millions of times faster!

This is because 232Th has a 14 billion-year half-life, but 232U has only an 74 year half-life!

Once it starts down "the hill" it gets to thallium-208 (the gamma emitter) in just a few weeks!

The Basics: Design Choices
Breeder vs Converter?

- **Breeder**
- Makes its own fuel after startup
- If “just enough” called Break Even
- Requires processing to continuously remove fission products
- No enrichment plants once established
- **Converter**
- Needs annual fissile makeup
- Skips fuel processing
- Much less R&D needed
- Core design simplified

The Basics: Design Choices *Single Fluid vs Two Fluid?*

- **Single Fluid**
- Everything in a one carrier salt
- Core design often simpler
- Processing to remove fission products the most complex (i.e. for breeders)
- **Two Fluid**
- Blanket salt for thorium, Fuel salt for the U233 it produces
- Fission product removal much simpler
- Core design “was thought” to be complex
- Need to verify barrier materials

The Basics: Design Choices
Harder or Softer Spectrum?

- **Harder Spectrum** (fast)
- Can skip graphite use
- Easier to breed
- Takes far more fissile material to startup
- Avoiding neutron “leakage” can be difficult
- **Softer Spectrum**
- Control is easier
- Much smaller fissile startup
- Must remove fission products faster to breed

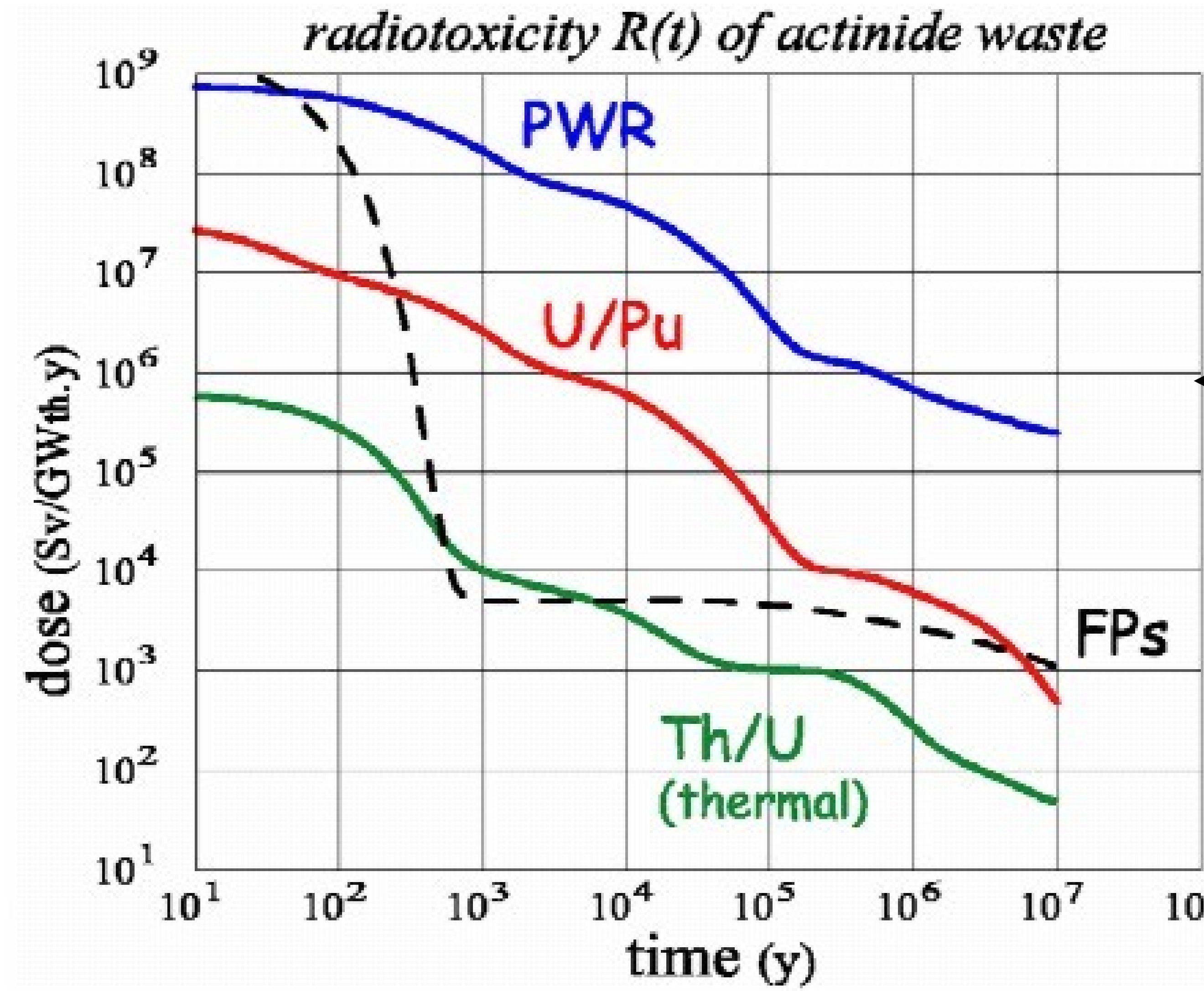
Advantages of all Molten Salt Reactors
Resource Sustainability

- Once started breeder designs only require minor amounts of thorium (about 1 tonne per GWe year)
  - 30 k$ of thorium = 500 M$ electricity
- Converter designs are simpler and only require modest amounts of uranium
  - Typically 35 tonnes U per GWe-year versus 200 tonnes for LWRs
  - Fuel cycle cost under 0.1 cents/kwh

Radiotoxicity PWR vs FBR* vs MSR*

*Assuming 0.1% Loss During Processing

Data and graph from Sylvain David, ***Institut de Physique Nucléaire d'Orsay***



PWR U Ore

DMSR U Ore

MSBR Th Ore

FPs
Fission
Products

Turns waste management into 500 year job, not million year

Rapid Deployment Capability

- ***What fissile to start and how much?***
- No U233 available, Spent Fuel Pu limited
- Fast Spectrum Single or 1 ½ Fluid require much more (up to 8 tonnes/GWe)
- Two Fluid Breeder, any Denatured design can start with Low Enriched Uranium

- ***Is small power feasible? 100 MWe?***
- Two Fluid designs with full blankets, YES
- Single Fluid graphite Converter, YES
- Single Fluid graphite Breeder, VERY HARD
- Single Fluid Fast Breeder, VERY HARD

Reactor	Lifetime Uranium Ore (t)	Annual Uranium Ore (t)	Annual Ore Costs **50$/kg U**	Annual Fuel Costs **50$/kg U**	Annual Fuel Costs **5000$/kg U**
LWR	**6400**	200	8.5 million	~40	~880
LWR with U-Pu Recycle	**4080**	125	5.3		
Sodium Fast Breeder	**2400** **If start up on ^{235}U**	1			
DMSR Converter	**1800**	35	1.5	~6 0.001$/kwh	~155 <0.02$/kwh
DMSR single U recycle	**1000**	35	1.5	~6	~155

Based on 0.2% tails, 75% capacity factor, 30 year lifetime

LWR data from “A Guidebook to Nuclear Reactors” A. Nero 1979

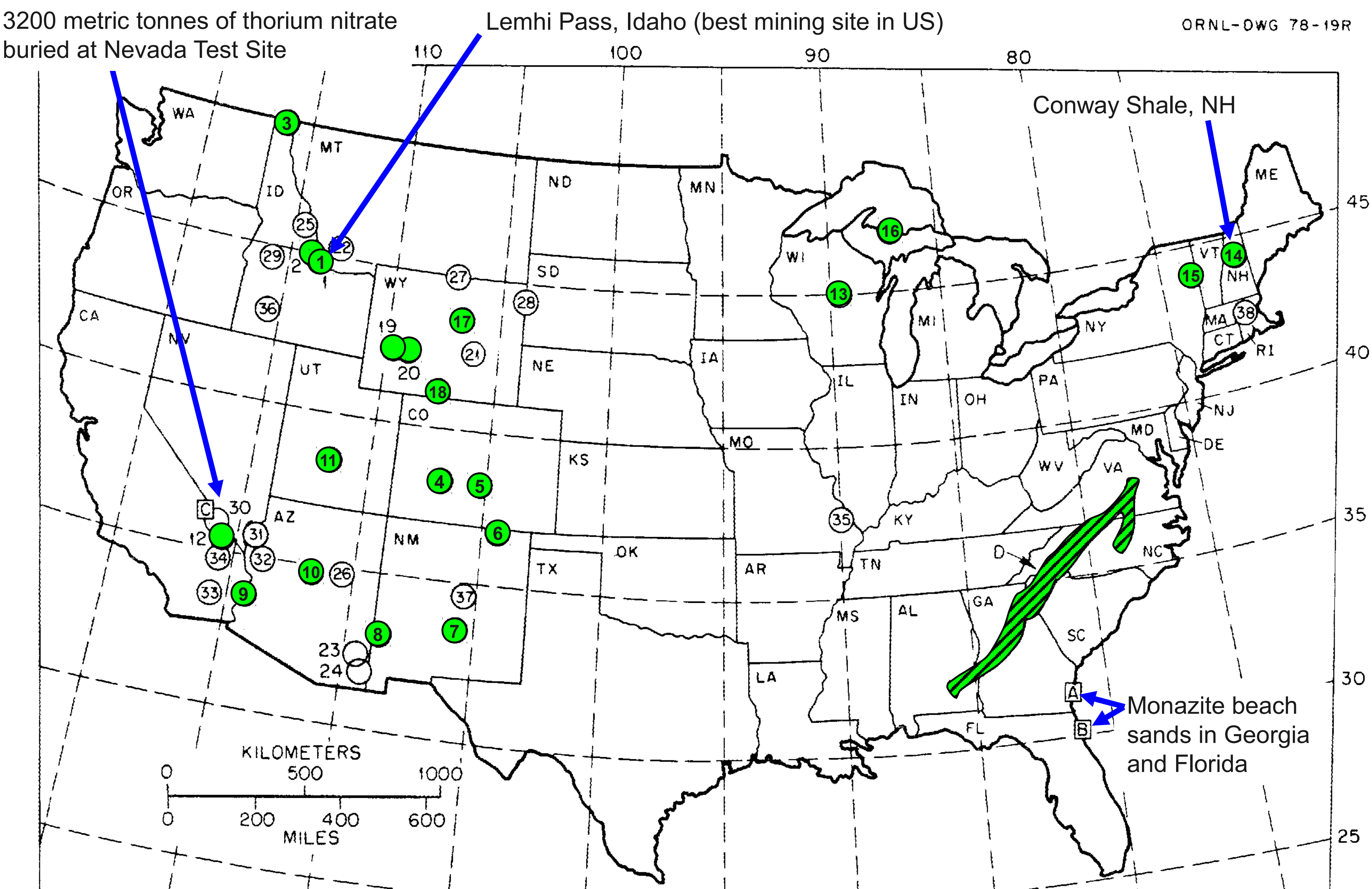
3.9 million$ annual enrichment costs for DMSR at 110$/SWU

At $5000/kg, uranium from sea water likely feasible and unlimited resource

1950s and 1960s Design Priorities

- **Safety – No problem…**
  - If we engineer it right, do proper maintenance and extensively train our staff "There is NO safety issue"
- **Power Costs – Important**
- **Resources – Extremely Important**
  - We will run out of uranium by the 1980s
  - LWRs OK for now but we will need breeder reactors
- **Rapid Deployment – Important**
  - Power needs expected to continue to rise exponentially so breeder reactors must have very short doubling times
- **Proliferation Resistance**
  - What?
- **Long Term Radiotoxicity**
  - What?
- **R&D Requirements**
  - Every concept needs plenty but funding is plentiful

Thorium Resources in the United States

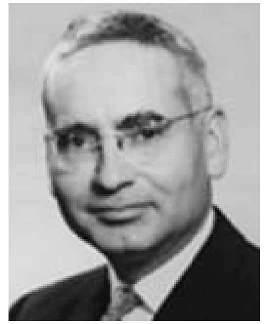


Liquid Fluoride Thorium Reactor Conclusions

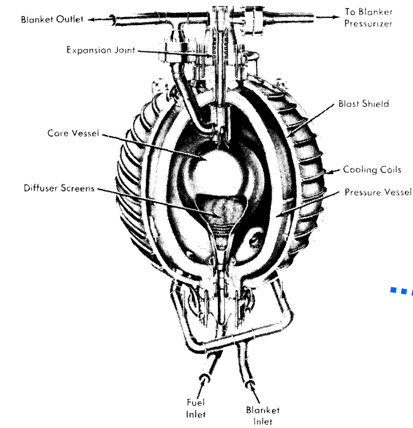
- **Thorium is abundant, has incredible energy density, and can be utilized in thermal-spectrum reactors**
  - World thorium energy supplies will last for tens of thousands of years at very least
- **Solid-fueled reactors have been disadvantaged in using thorium due to their inability to continuously reprocess**
- **Fluid-fueled reactors, such as the liquid-fluoride reactor (LFTR), offer the promise of complete consumption of thorium (and TRU waste) in energy generation**
- **The world would be safer with thorium-fueled reactors**
  - Not an avenue for weapons production, no need for enrichment facilities
- **The US should adopt a new "business model" for nuclear power for the country's long term strategic needs**
  - Laws and Regulations need to be updated to allow small modular reactors
  - **Experimental R&D needs to be re-started**
  - No two experts or two nations will rank priorities the same, so multiple options are the best avenue

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)

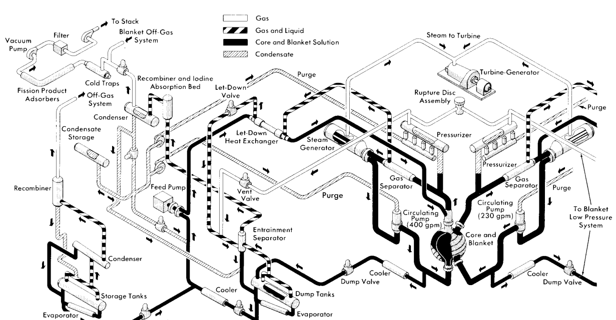
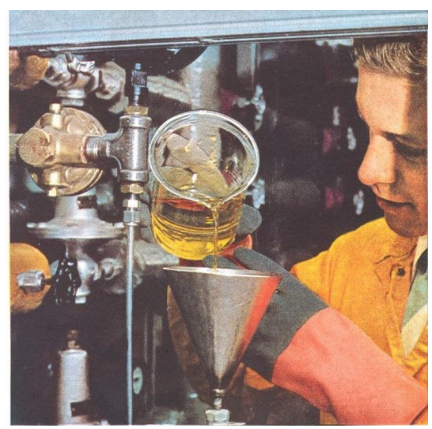


FIG. 7-7. Flowsheet of HRE-2.



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

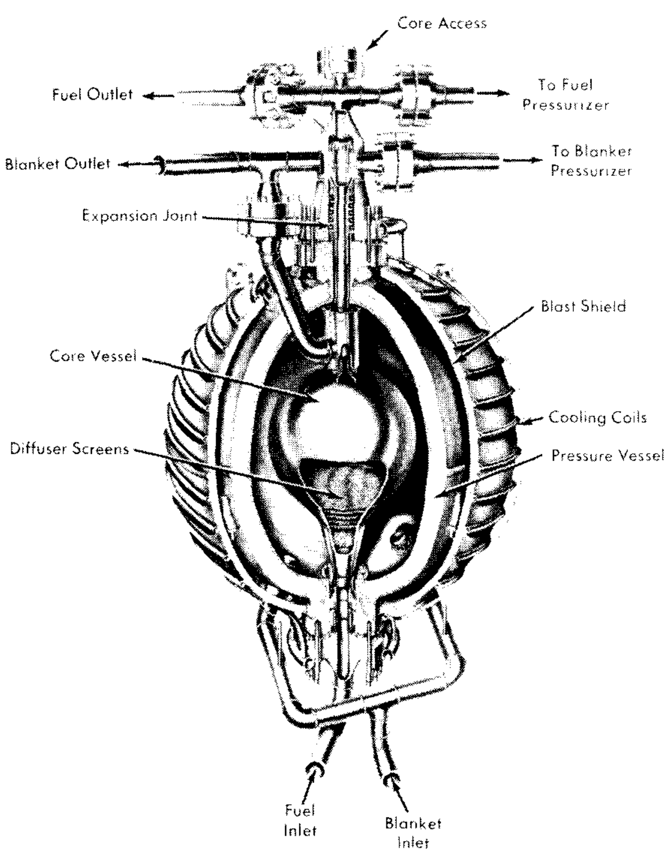
1959 – AEC convenes "Fluid Fuels Task Force" to choose between aqueous homogeneous reactor, liquid fluoride, and liquid-metal-fueled reactor. Fluoride reactor is chosen and AHR is canceled

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

Fluid-Fueled Reactors for Thorium Energy

Aqueous Homogenous Reactor (ORNL)

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



Liquid-Fluoride Reactor (ORNL)

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

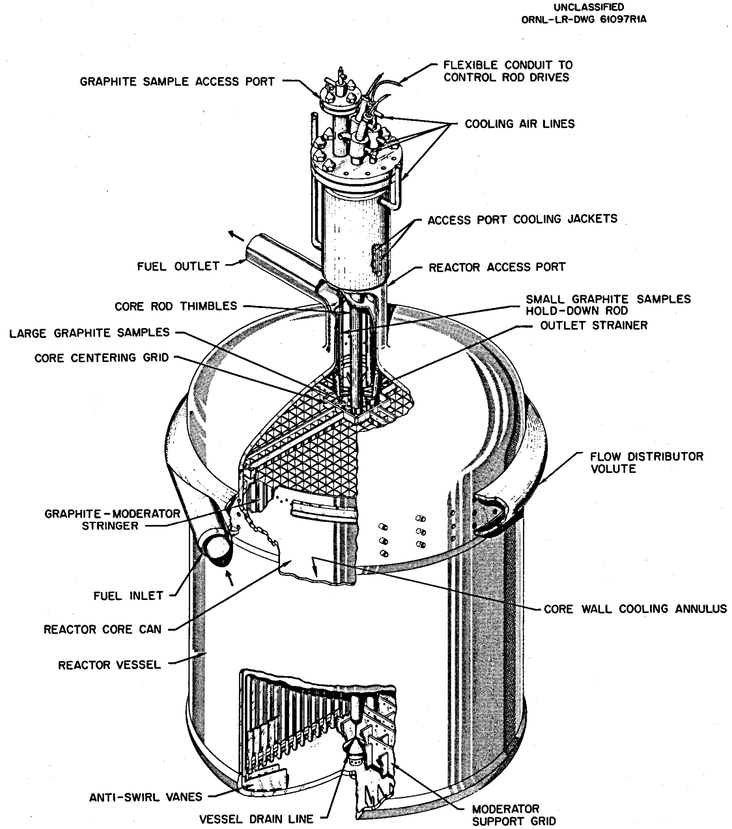
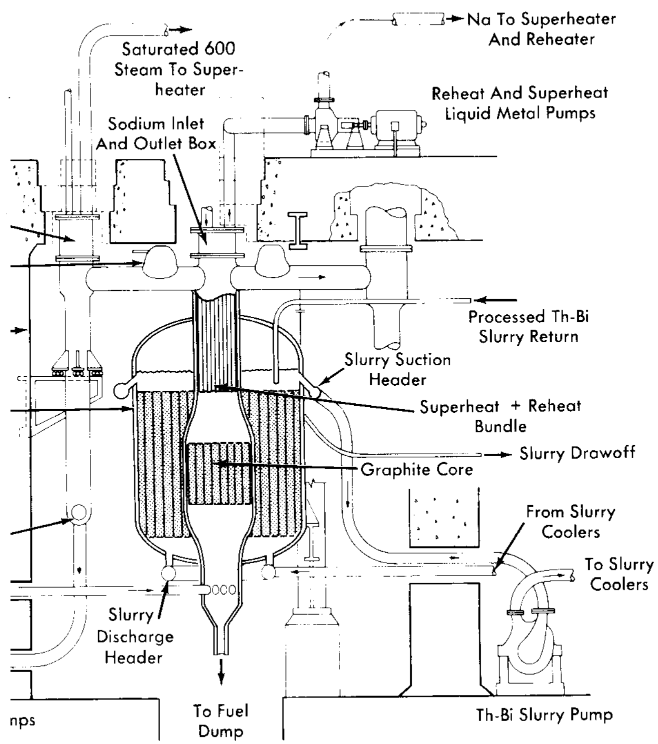


Fig. 6. MSRE Reactor Vessel.

Liquid-Metal Fuel Reactor (BNL)

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



Ondřej Chvála, chvala@bnl.gov

What about Long Island? Ask EPA!

Where does your electricity come from?
http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html

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.

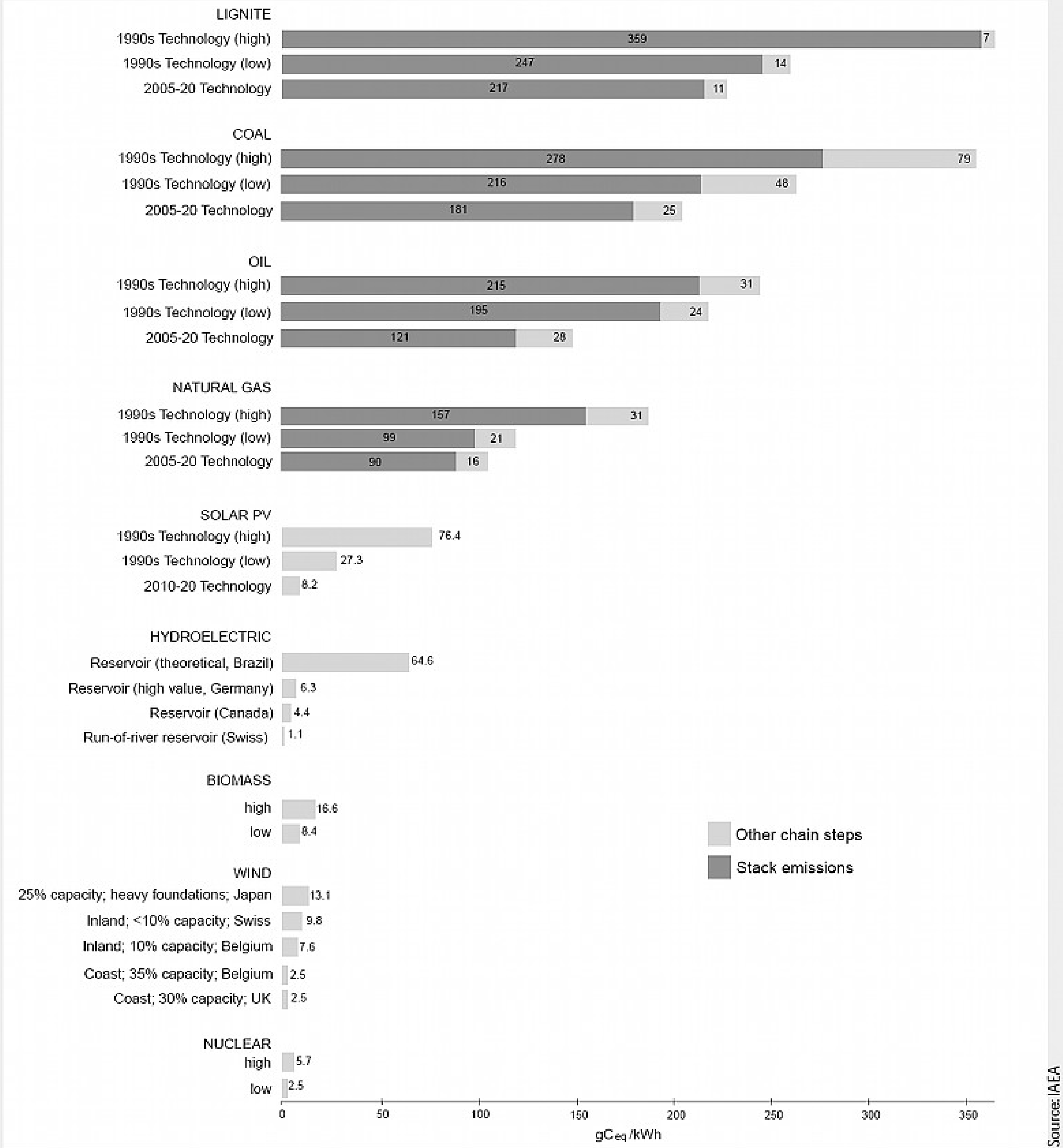
There is a NPP “around the corner”
http://en.wikipedia.org/wiki/Shoreham_Nuclear_Power_Plant

820 MWe nuclear plant was “replaced” by 2x 50kW wind mills (+ oil + gas)

Similar case in Austria
Satirical 'movement' **Start Zwentendorf!**
http://plarmy.org/zwentendorf/en/

Start Shoreham? E-mail me if interested!

RANGE OF TOTAL GREENHOUSE GAS EMISSIONS FROM ELECTRICITY PRODUCTION CHAINS



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 ccuses 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.

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)	Alternative Measures of Subsidy and Support: 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.

[1]Net 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

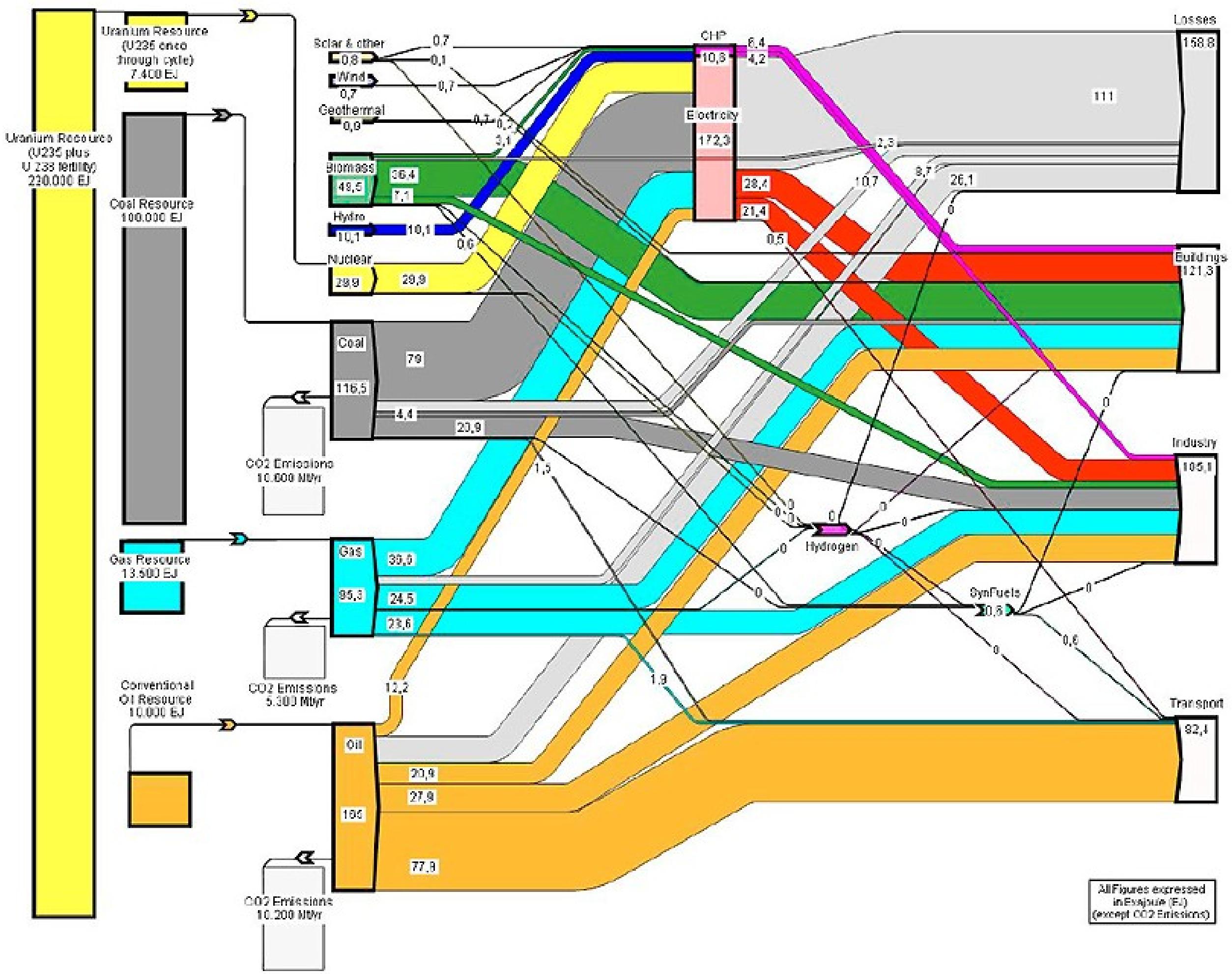
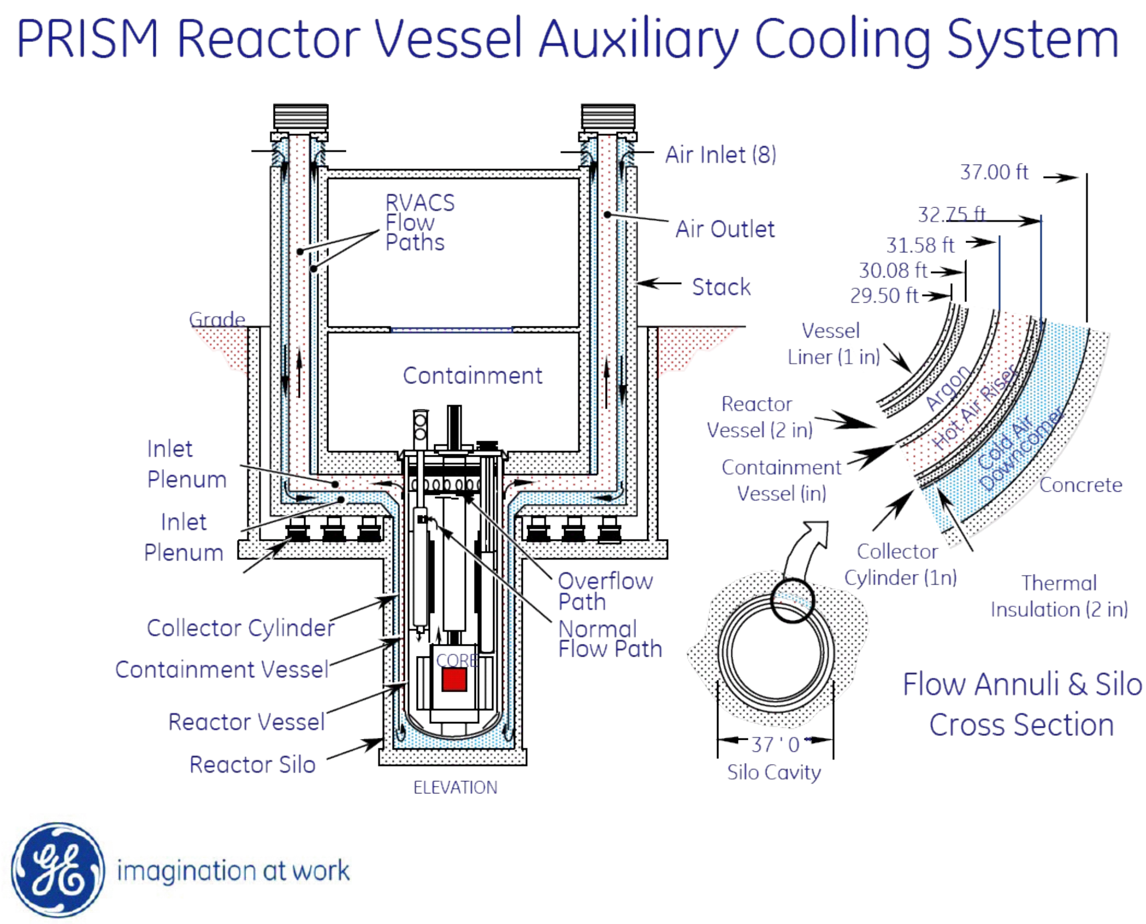


Figure 4.4: *Global energy flows (EJ in 2004) from primary energy through carriers to end-uses and losses. Related carbon dioxide emissions from coal, gas and oil combustion are also shown, as well as resources (vertical bars to the left).*

http://nuclearstreet.com/blogs/nuclear_power_news/archive/2009/03/17/increase-in-thorium-reserves-alternative-to-uranium-for-nuclear-power-generation.aspx

GE-Hitashi PRISM



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 ºC).

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	

[a]Of metallic ion.

[b]Cross section for ^7Li.

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

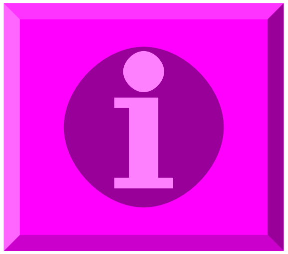
2008 electric power costs $/KWH (delivered)

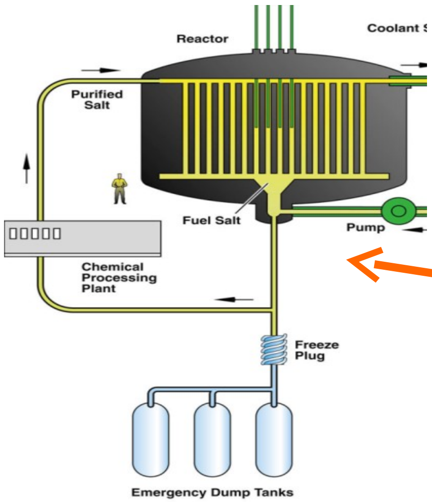
Guangdong	0.0720
Shanghai	0.0790

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!
Emulate Boeing mass production.

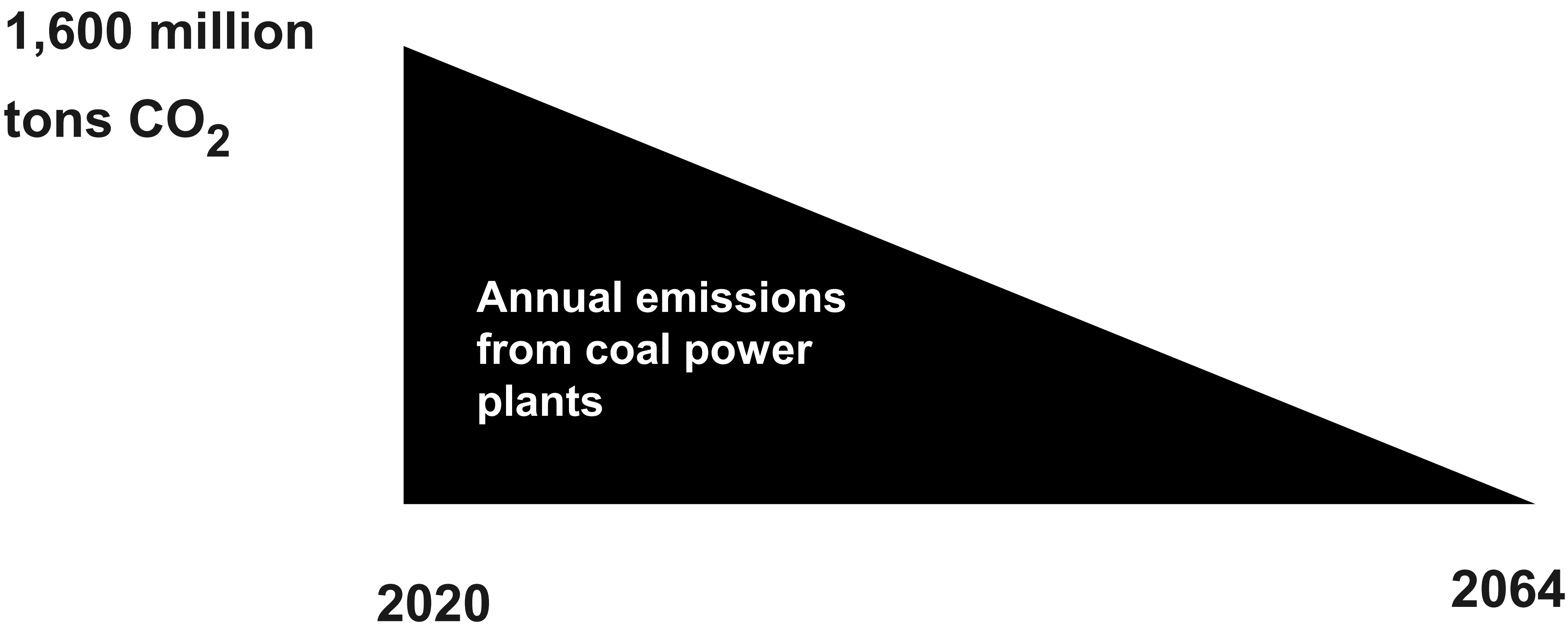
(*) Stolen from Robert Hargraves
http://rethinkingnuclearpower.googlepages.com/aimhigh

- 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.

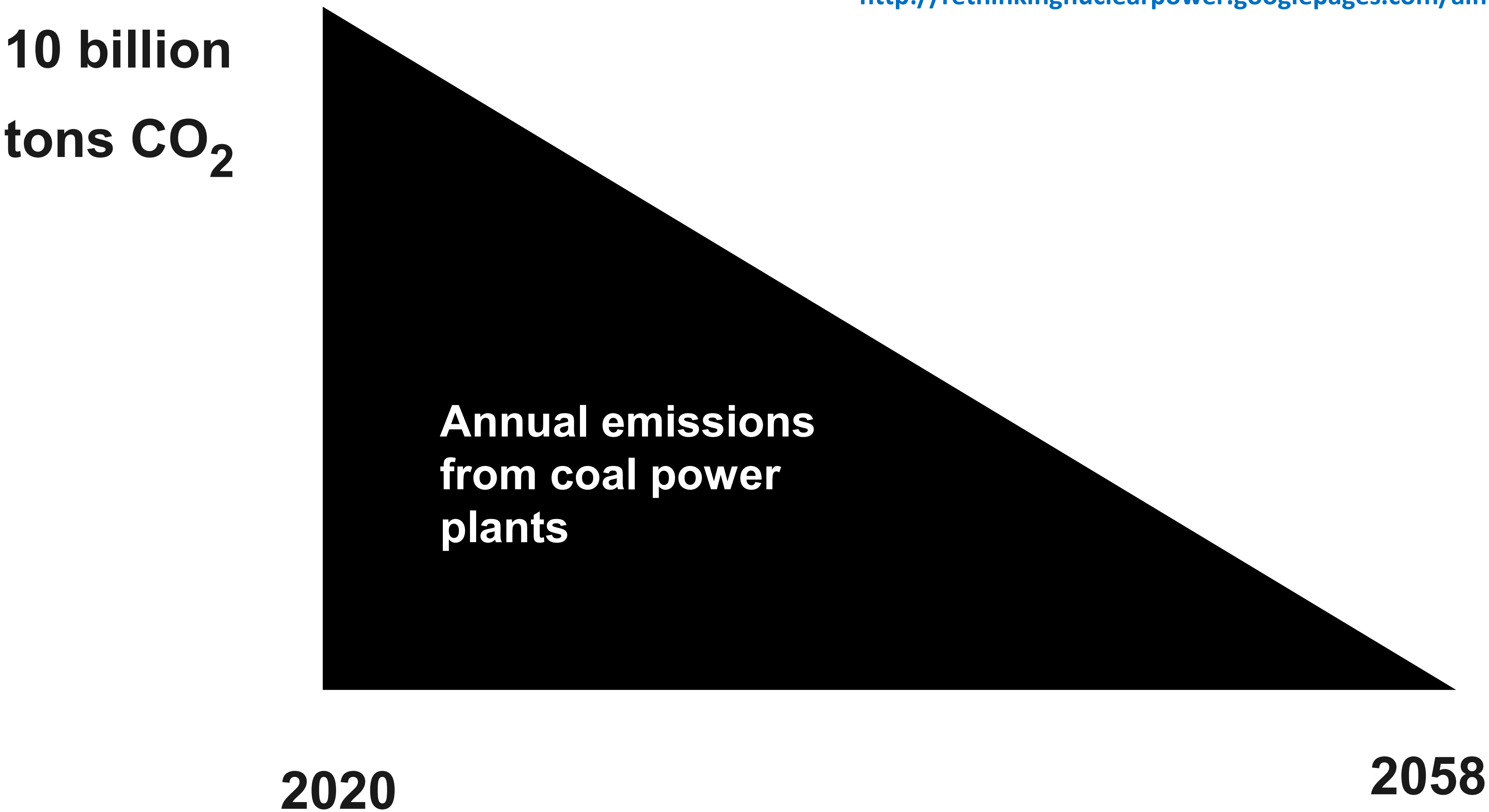
(*) Stolen from Robert Hargraves
http://rethinkingnuclearpower.googlepages.com/aimhigh



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

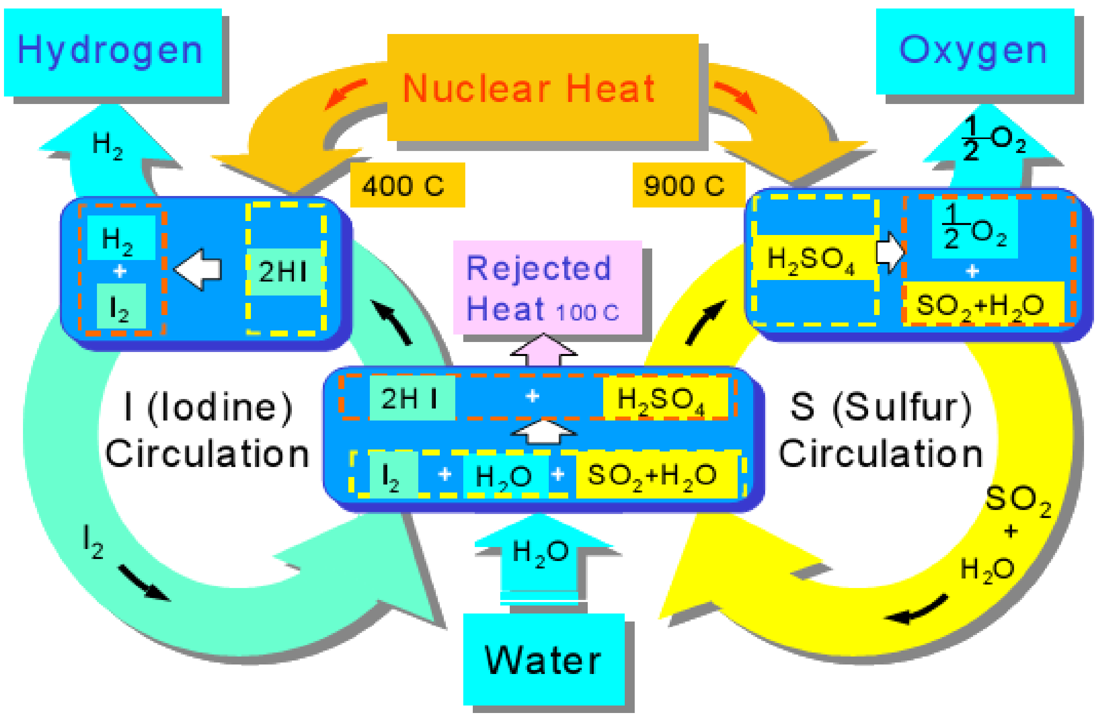


http://www.eia.doe.gov/pub/international/iealf/table63.xls

Aim High!
Make motor fuel cheaper than from oil.

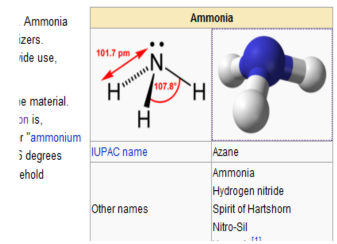
(*) Stolen from Robert Hargraves
http://rethinkingnuclearpower.googlepages.com/aimhigh

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

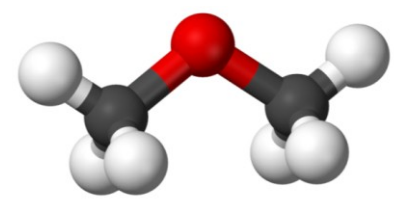


Alternatively start at 700°C with a less efficient process.

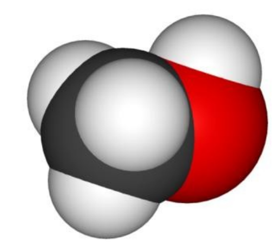
http://wwwtest.iri.tudelft.nl/~klooster/reports/hydro_slides_2003.pdf



Ammonia



Dimethyl ether for diesel

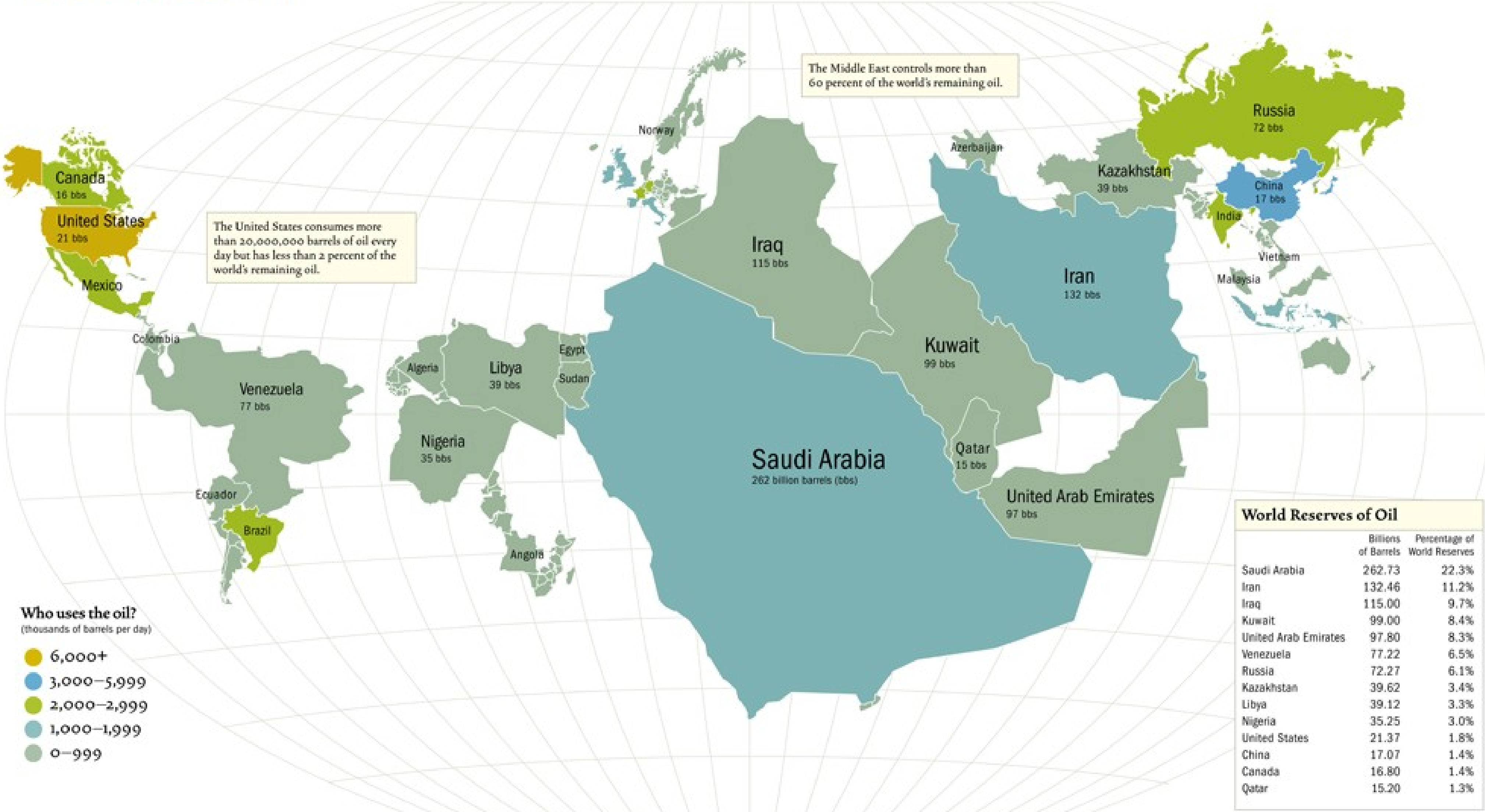


Methanol for gasoline

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

Ondřej Chvála, chvala@bnl.gov

Who has the oil?



World Reserves of Oil

	Billions of Barrels	Percentage of World Reserves
Saudi Arabia	262.73	22.3%
Iran	132.46	11.2%
Iraq	115.00	9.7%
Kuwait	99.00	8.4%
United Arab Emirates	97.80	8.3%
Venezuela	77.22	6.5%
Russia	72.27	6.1%
Kazakhstan	39.62	3.4%
Libya	39.12	3.3%
Nigeria	35.25	3.0%
United States	21.37	1.8%
China	17.07	1.4%
Canada	16.80	1.4%
Qatar	15.20	1.3%

Each country's size is proportional to the amount of oil it contains (oil reserves); Source: *BP Statistical Review* Year-End 2004 & Energy Information Administration