Thorium Use in Nuclear Power

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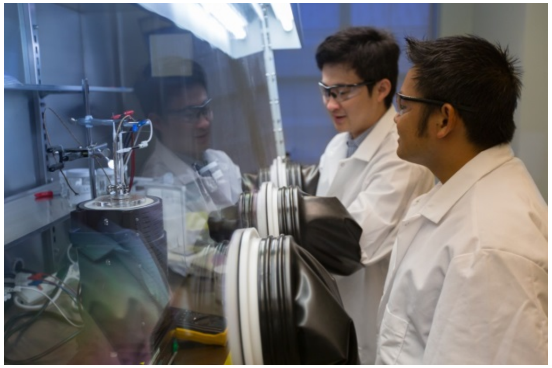
Brief Bio

- Education:
  - NRC Postdoctoral Fellow at Naval Research Laboratory, Washington D.C., 2001 – 2004;
  - Ph.D. Chemical Engineering from University of Maryland, College Park (2001); and
  - B.S. Nuclear Engineering from University of Maryland, College Park, (1997).

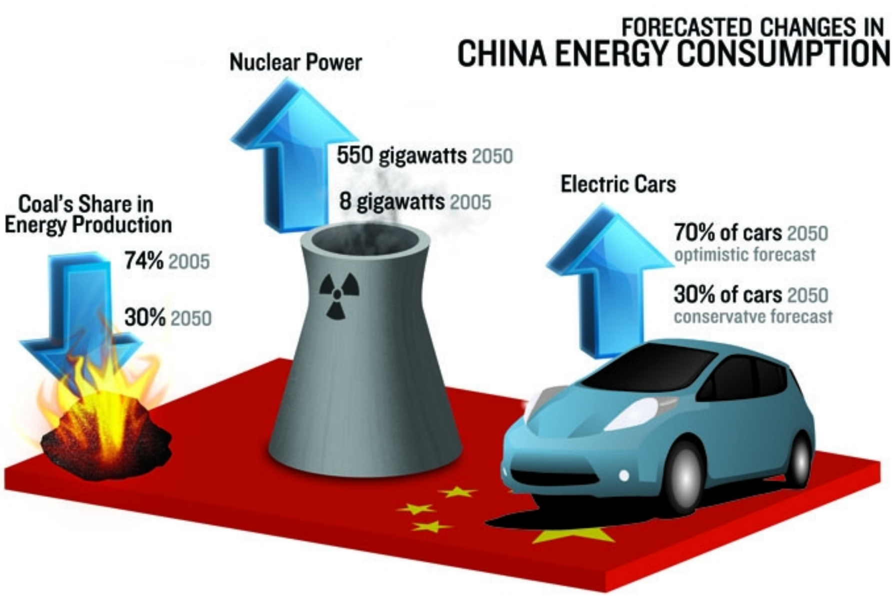


- Professional experience (teaching and conducting research in Nuclear Fuel Cycle since 2004):
  - Associate Professor, Mechanical and Nuclear Engineering, Virginia Commonwealth University, 2014 - Present
  - Associate Professor, Chemical & Materials Engineering and Nuclear Engineering Program, University of Idaho, 2013 – 2014
  - Assistant Professor, University of Idaho, 2007 – 2013
  - Research Engineer, Idaho National Laboratory, 2004 – 2007
- Over 17 peer-reviewed publications on molten salt systems.
- Over 30 presentations at national and international conferences on molten salt systems.

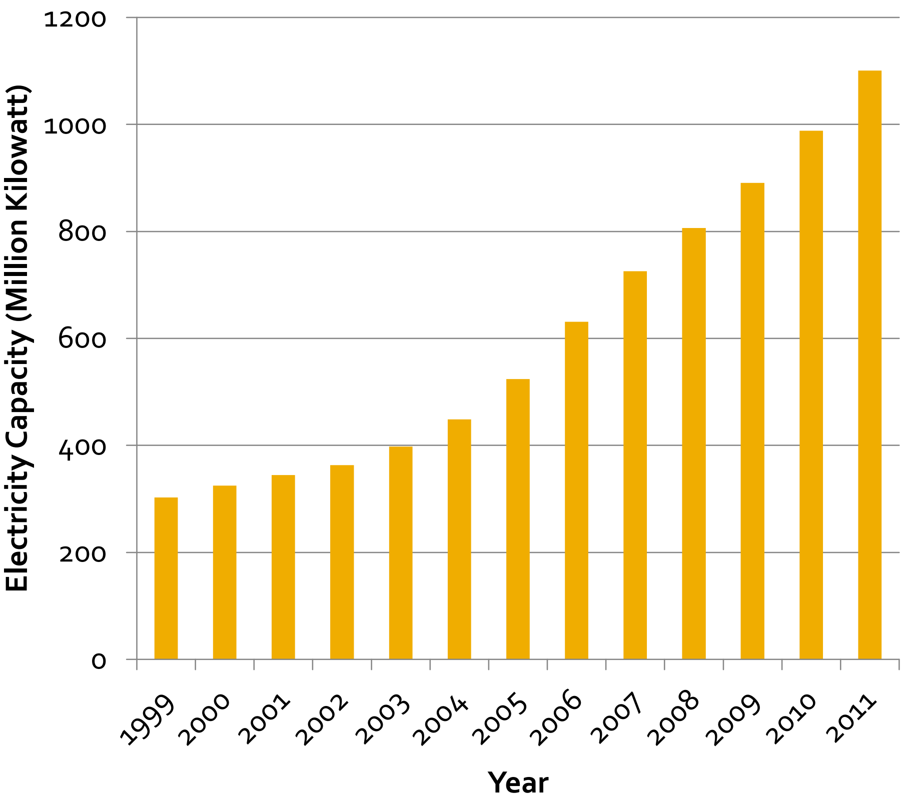
- Hobbies:
  - Climbing,
  - Backpacking & Hiking,
  - Backcountry Skiing,
  - Swimming, Road biking, and running

Example in Ongoing Challenges

- China's Energy Challenge—Reaching 3000 GW in 2030 on electricity demand (about 2 kW per person).

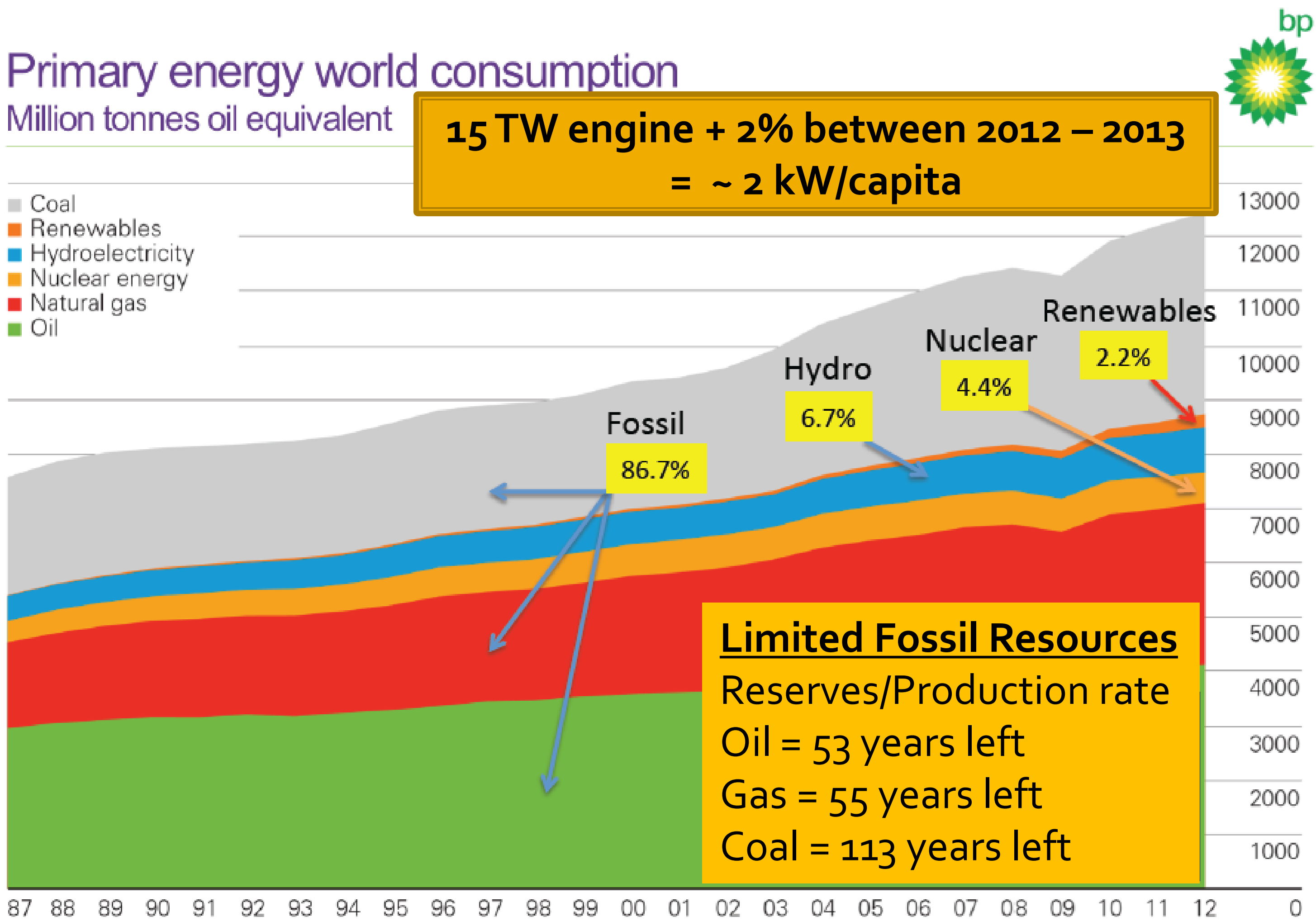


http://archive.dailycal.org/article.php?id=113056
August 9th, 2013



http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=2&aid=7&cid=regions&syid=1999&eyid=2011&unit=MK

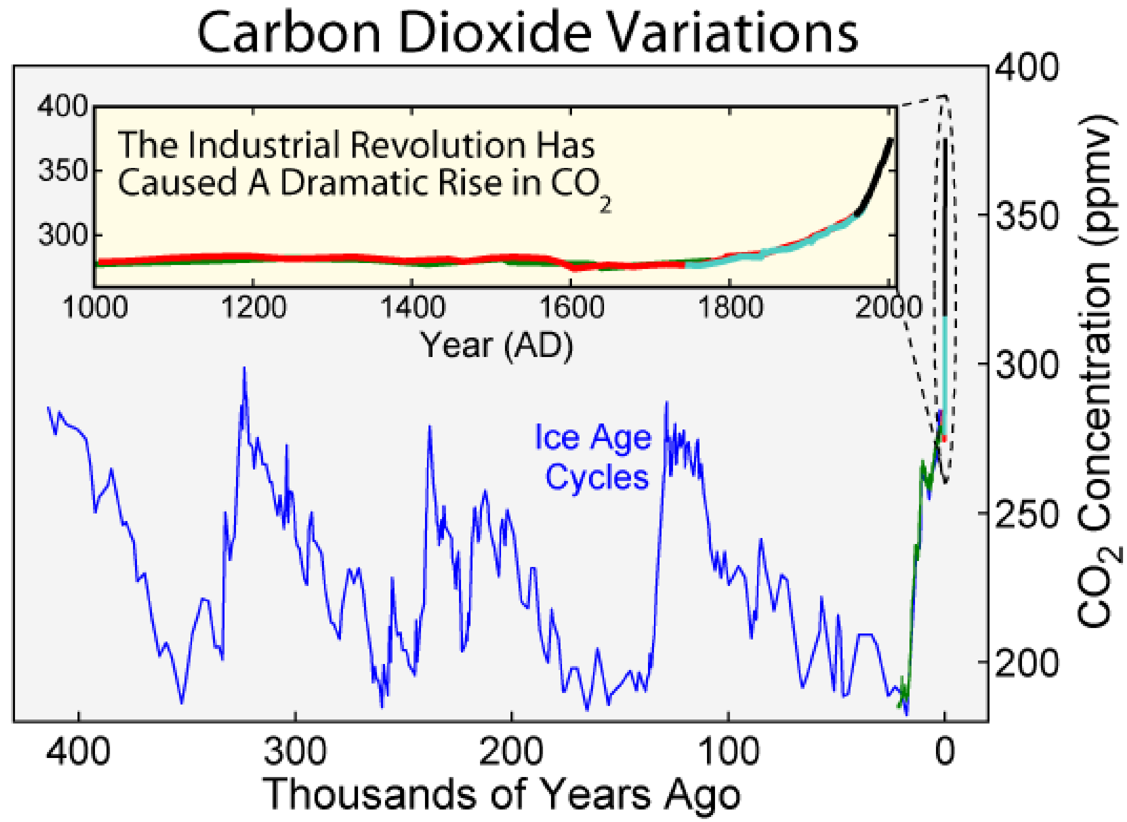
Primary Energy World Consumption



BP Statistical review of World Energy 2014

Global Warming

- Atmospheric CO_2 level has been increasing sharply (compare to the past 15 million years):



http://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere

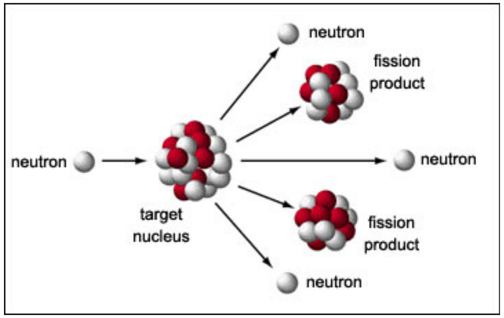
Air Pollution

- 54 billion U.S. $ in 2013 health care expenses—in Europe for burning coal.
- 1.2 Million premature deaths in China (2013) due to air pollution.

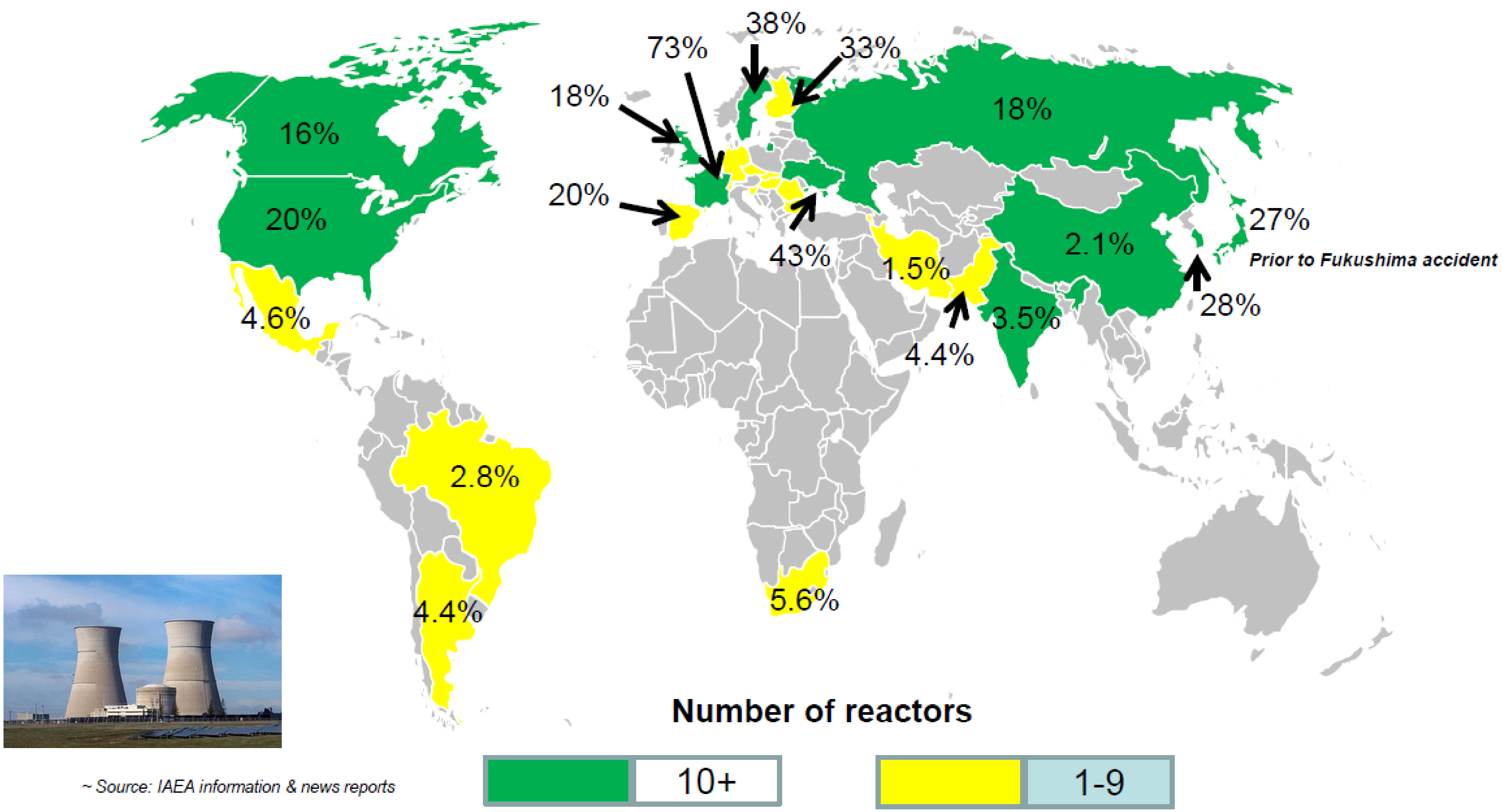
http://www.nytimes.com/2013/04/02/world/asia/air-pollution-linked-to-1-2-million-deaths-in-china.html?_r=0
http://www.huffingtonpost.com/2013/10/15/europe-air-pollution-wood-fires-diesel-cars_n_4099578.html

Solution? –Energy Innovations!?

- Innovation = Fundamental research + Applied research
- Wind and Solar energy → contribution to the world energy by a factor 130 or more
  - Not realistic→ Space? Storage? Cost? Distribution?
  - Idaho? Utah? Wyoming?
- What about Nuclear?
  - Energy R&D → Nuclear Fission must NOT be left behind



Existing Nuclear Commercial Power Reactors (13.8% World Wide/21.4% OECD)



~ Source: IAEA information & news reports

The Organization for Economic Co-operation and Development (OECD) – 34 nations

OECD: Members and Partners

- [Australia]
- [Austria]
- [Belgium]
- [Canada]
- [Chile]
- [Czech Republic]
- [Denmark]
- [Estonia]
- [Finland]
- [France]
- [Germany]
- [Greece]
- [Hungary]
- [Iceland]
- [Ireland]
- [Israël]
- [Italy]
- [Japan]
- [Korea]
- [Luxembourg]
- [Mexico]
- [Netherlands]
- [New Zealand]
- [Norway]
- [Poland]
- [Portugal]
- [Slovak Republic]
- [Slovenia]
- [Spain]
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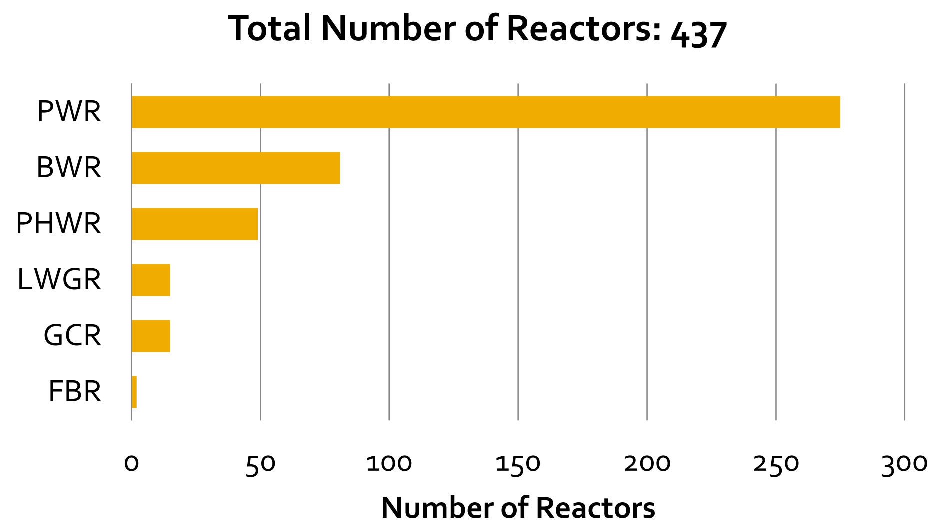
- [Switzerland]
- [Turkey]
- [United Kingdom]
- [United States]

Common Reactor Designs and Current Operating Reactors in 30 Countries

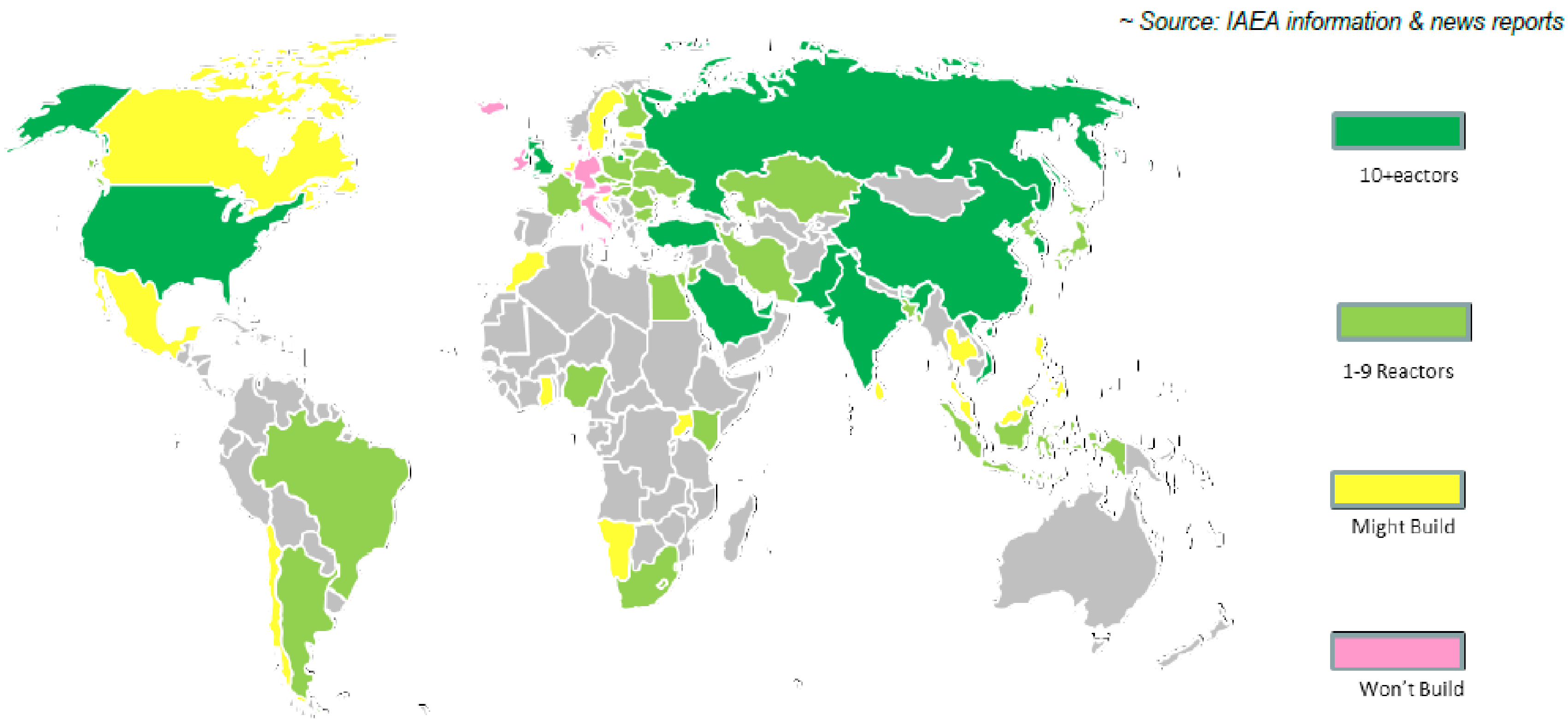
VCU



Reactor Type	Reactor Type Descriptive Name	Number of Reactors	Total Net Electrical Capacity [MWe]
FBR	Fast Breeder Reactor	2	580
GCR	Gas-Cooled, Graphite-Moderated Reactor	15	8045
LWGR	Light-Water-Cooled, Graphite-Moderated Reactor	15	10219
PHWR	Pressurized Heavy-Water-Moderated and Cooled Reactor	49	24592
BWR	Boiling Light-Water-Cooled and Moderated Reactor	81	75958
PWR	Pressurized Light-Water-Moderated and Cooled Reactor	275	255110
Total		437	374504

http://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx

Global Nuclear Construction Plans

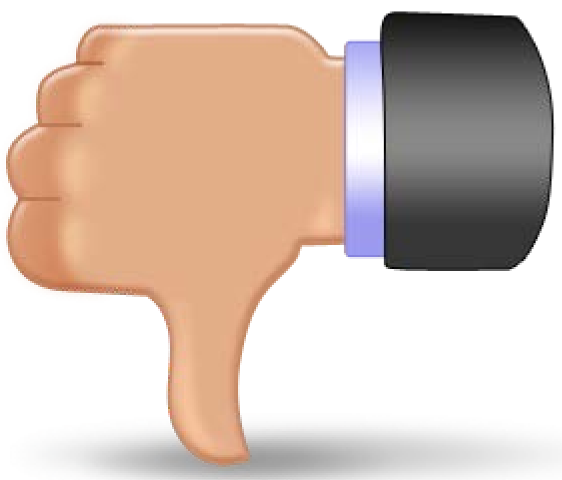


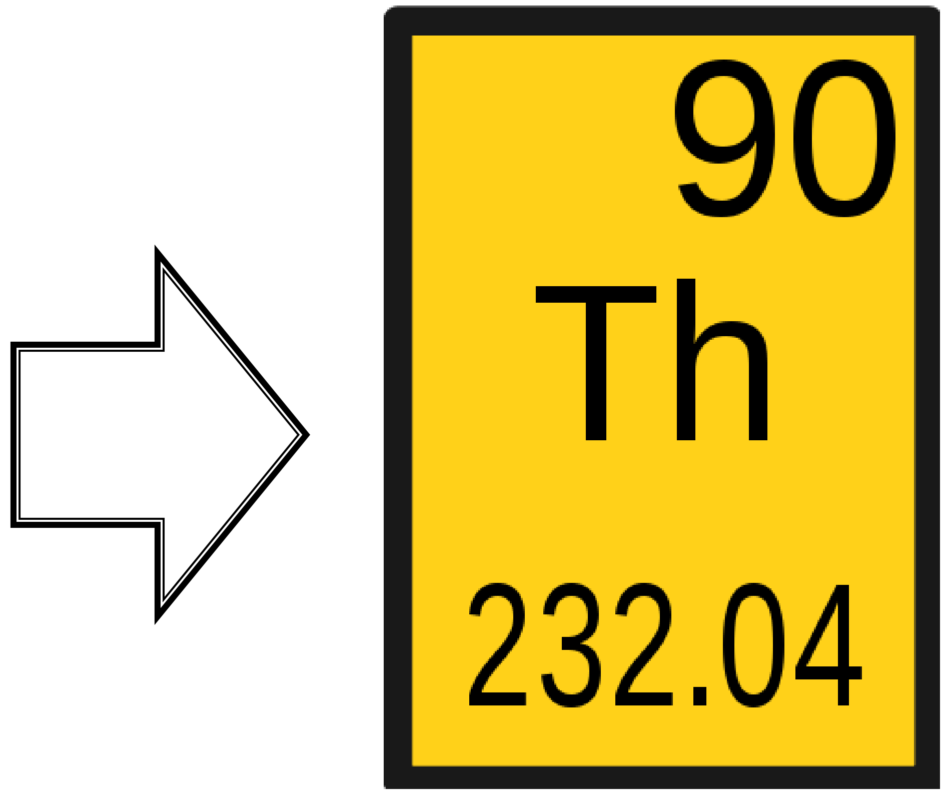
- 71 reactors currently under construction in 15 countries (28 in China)
- 172 reactors planned in 26 countries over next 8-10 years
- 309 reactors proposed in 35 countries over next 15 years

Shortcomings!

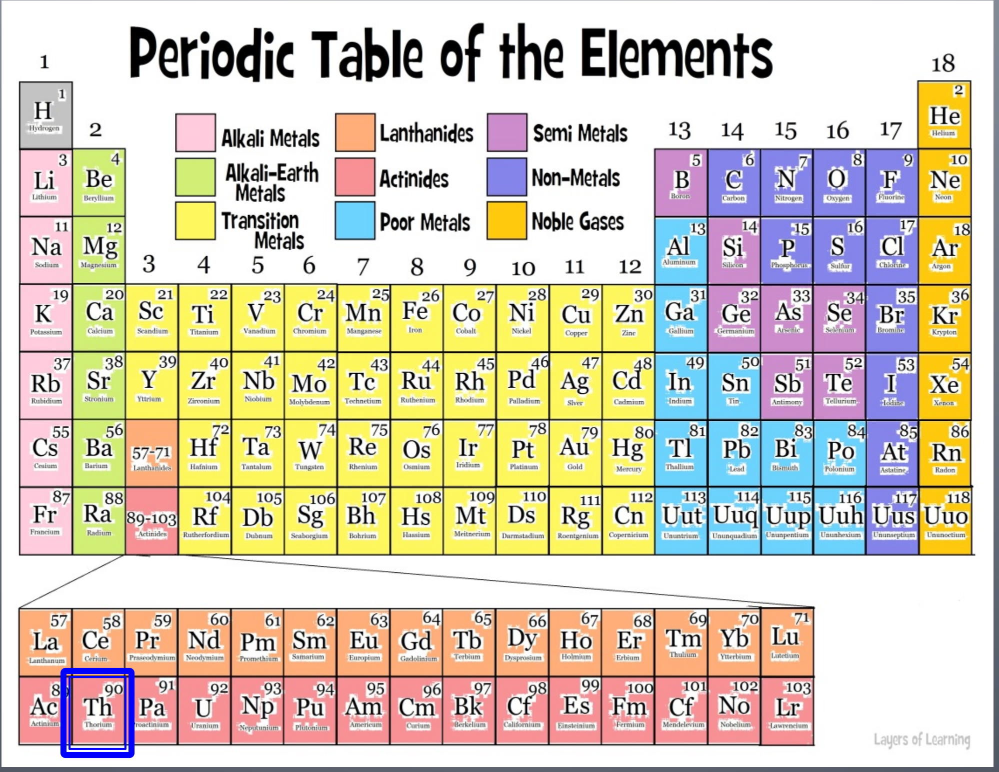
- Present generation of uranium power plants must be reconsidered:
  - Accidents (Chernobyl, TMI, Fukushima).
  - Waste Management (Storage over ≤ one million years, the only option developed so far).
  - Proliferation of nuclear weapons (uranium = ).
  - Sustainability (< 100 yr at present rate).

Is it possible to make nuclear energy acceptable to society?





Why Thorium?



Discovered in 1828 by the Jons Jacob Berzelius, naming it after the Norse god of thunder and weather, Thor.

90 232.04 Th Thorium

Physical properties as an atomic nucleus

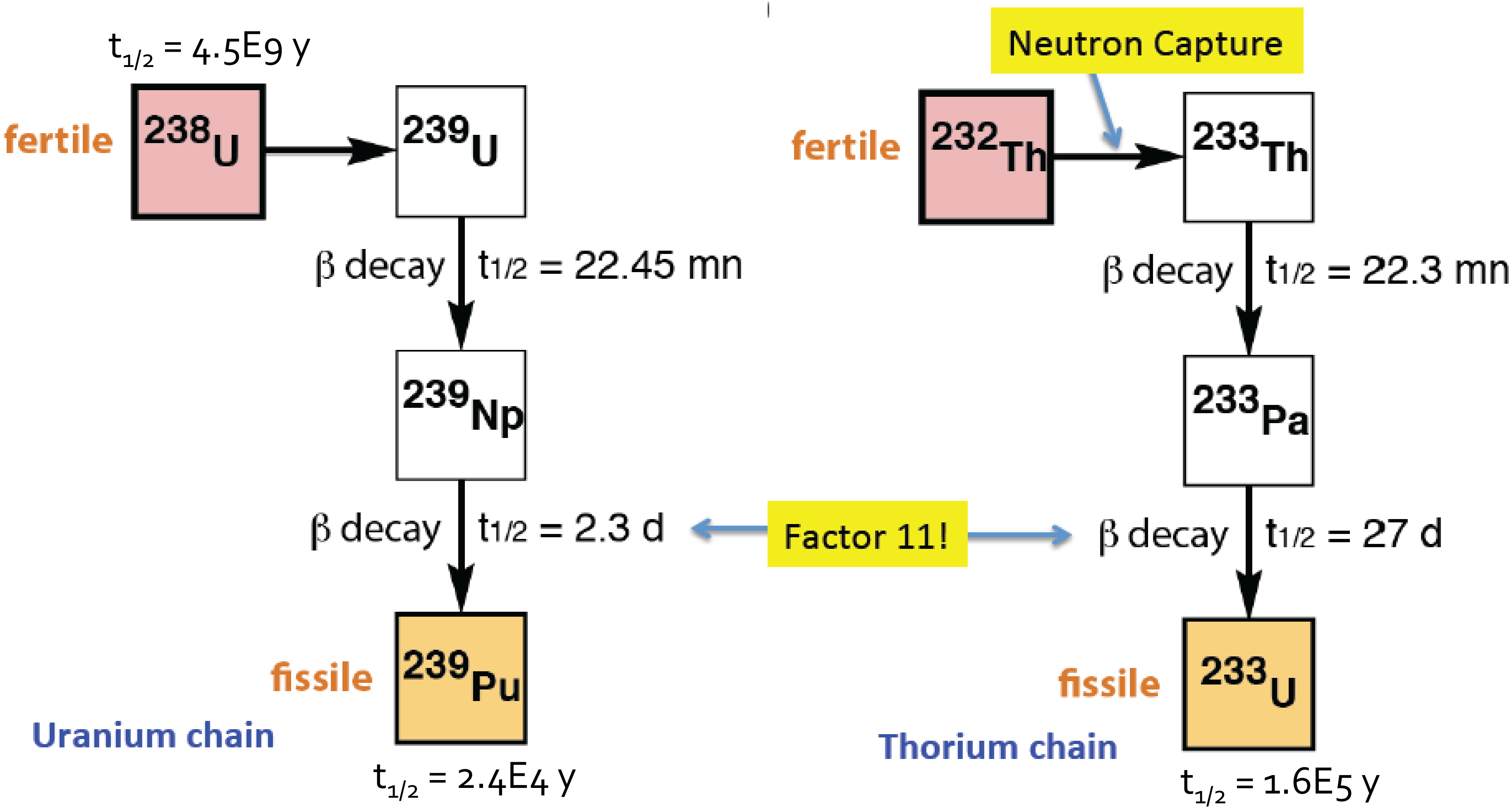
VCU

- Natural thorium is isotopically pure, alpha decay with a $t_{1/2}$ of 14 billion (1.4×10^{10}) years (almost stable, no enrichment)
- It undergoes natural disintegration and is eventually converted through a 10-step chain of isotopes to ^{208}Pb, a stable isotope.
- Th-232 and U-238 are fertile materials.
- An absorption of a neutron by U-238 will generate Pu-239, so **U-233 is generated from Th-232**.

Thermal range (0.025 eV)

	Th-232	Th-230	U-238	U-235	U-234
Abundance	100%	ε	99.275%	0.720%	0.005%
σ_c barns	7.4	23.2	2.3	98.4	100.2
σ_f barns	ε	0.0012	-	**584**	0.6

Fission Energy



Pa = Protactinium Np = Neptunium

Physical properties as an atomic nucleus

- Pa-233 can capture a neutron and the formation of U-233 is in competition with the formation of U-234.

$$^{232}\text{Th} + \text{n} \rightarrow {}^{233}\text{Th}(22\text{m}) \rightarrow {}^{233}\text{Pa} + \text{n} \rightarrow {}^{234}\text{Pa}(6.7\text{h}) \rightarrow {}^{234}\text{U}$$

- U-233 has higher neutron yield per neutron absorbed (η) than either U-235 or Pu-239.

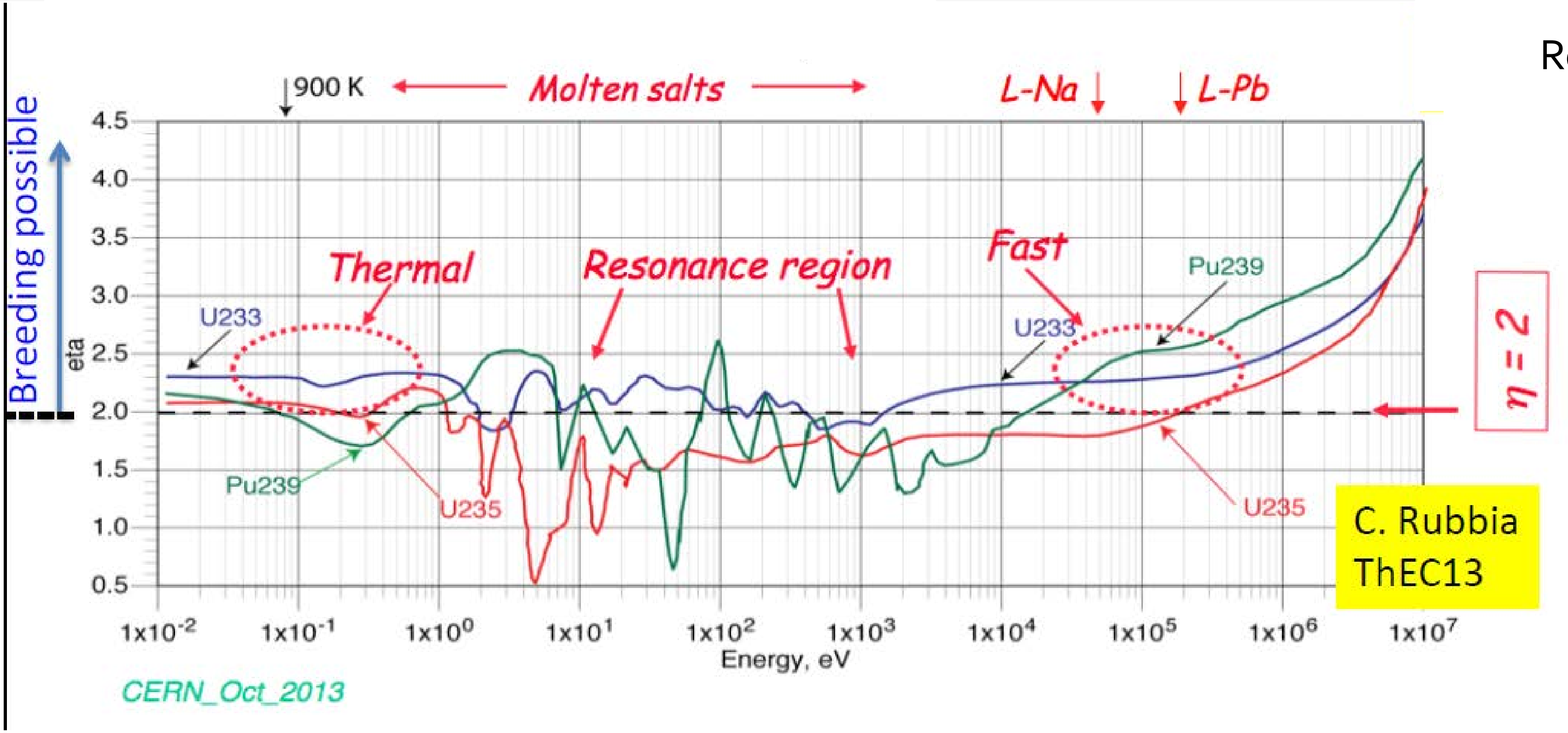
Reproduction factor

- In a standard PWR,

$$\eta_{^{233}\text{U}} = 2.27 \qquad \eta_{^{235}\text{U}} = 2.06 \qquad \eta_{^{239}\text{Pu}} = 1.84$$

Possible to Achieve Breeding in Today's Reactors

Ref: [10]



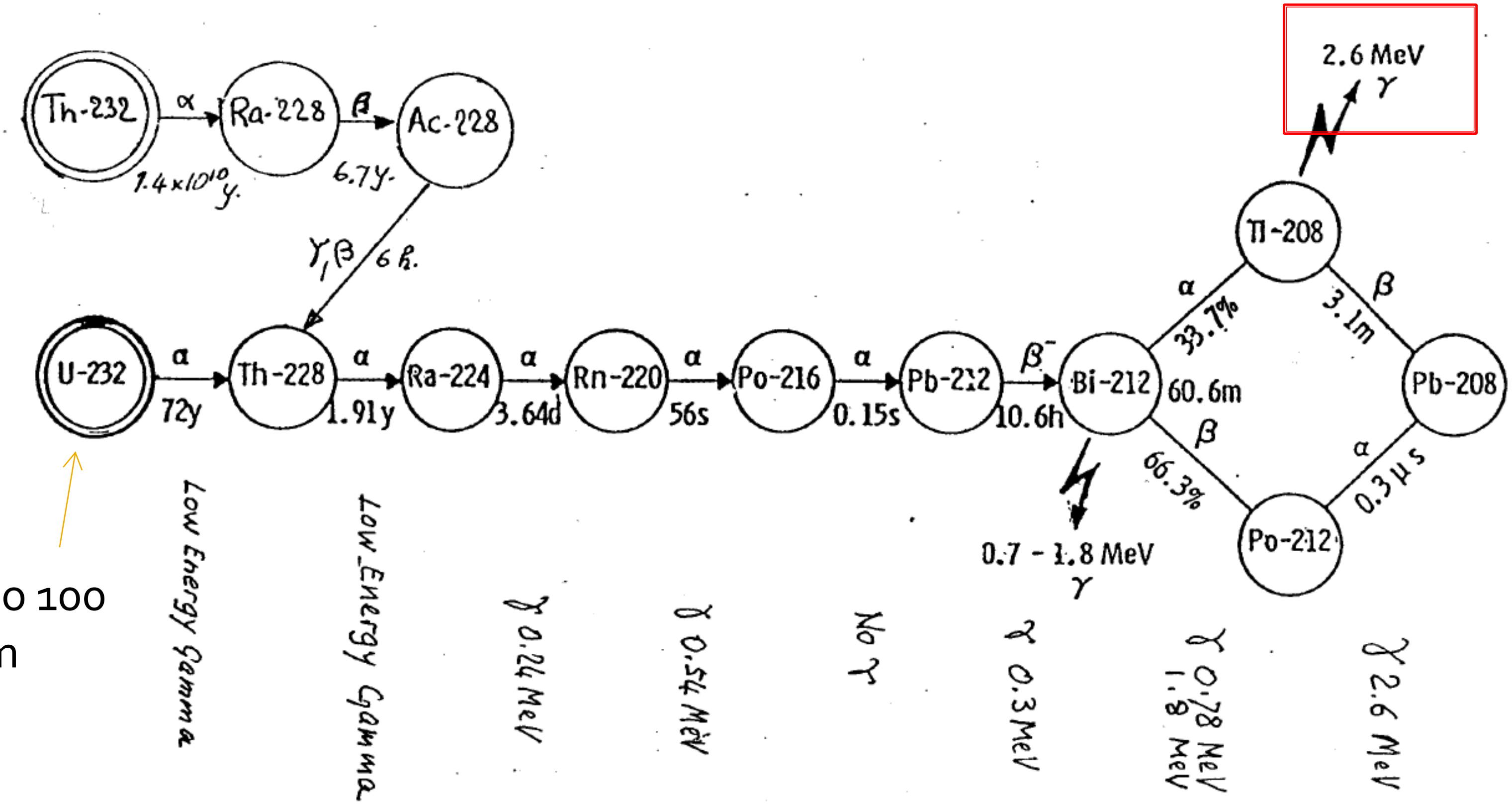
- ^{233}U is an excellent for a breeder reactors.

$$\eta = \frac{\text{Fission neutrons produced}}{\text{Absorption of a thermal neutron}}$$

Physical properties as an atomic nucleus

- To generate U-233, fissile materials (such as U-235 or Pu-239) are required to provide the neutrons.
- After being discharged from the reactor, used fuel can be reprocessed.
- The minor actinides produced in a thorium/U-233 fuel cycle have much shorter decay chain than with U-238/U-235 or plutonium fuel cycles → good for waste management!
- Fissile properties of U-233 implies that only a small amount of the metal can be used to prepare a nuclear weapon. The small amount of spontaneous neutron would permit to manufacture rather simple weapon types.
- One of the [principal drawbacks]() of the thorium cycle is U-232 production through various nuclear reaction on Th-232 and U-233.

The U-232 Decay Chain



10 to 100 ppm

First: $^{232}Th(n,2n) \rightarrow {}^{231}Th(\beta) \rightarrow {}^{231}Pa(n,\gamma) \rightarrow {}^{232}Pa(\beta) \rightarrow {}^{232}U$

Second: $^{232}Th(n,\gamma) \rightarrow {}^{233}Th(\beta) \rightarrow {}^{233}Pa(n,2n) \rightarrow {}^{232}Pa(\beta) \rightarrow {}^{232}U$

Third: $^{233}U(n,2n) \rightarrow {}^{232}U$

Chemical Characteristics of ^{233}U

- U-233 is chemically identical to natural, depleted and enriched uranium.
- As a consequence of its shorter half-life, the U-233 isotope has a higher specific radioactivity than the naturally occurring isotopes of uranium.
- Certain radiation-induced chemical reactions are faster in uranium containing significant quantities of U-233.
- This is important in a long-term storage—the higher radiation levels of U-233 require that storage containers and that, through radiolysis, could degrade to form potentially explosive concentrations of hydrogen gas.

Physical Characteristics

Th
90
232.04
Thorium

Recovering only 1 ppm, that is 1.2E8 tons, would provide the present world power consumption of 15 TW, for 18,000 years.

- Often a by-product of mining for rare earths (lanthanides + scandium and yttrium), tin, coal and uranium tailings

- Thorium dioxide (ThO_2) has the highest melting point (3300 °C compared to 2865 °C for UO_2) of all oxides and is one of the best refractory materials

- Metallic thorium has a melting point of 1750 °C compared to 1130 °C for metallic uranium

Estimated World Thorium Resources

Country	Tonnes
India	846,000
Brazil	632,000
Australia	595,000
USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Sweden	50,000
Kazakhstan	50,000
Other countries	1,725,000
World total	**6,355,000**

Source: OECD NEA & IAEA, *Uranium 2014: Resources, Production and Demand* ('Red Book')[1], using the lower figures of any range

90
Th
232.04

1890's to 1930's

- Originally the rare earth ore monazite was mined for Thorium—to make gas mantles.
- The rare earths were mostly a curiosity for many Chemists.
- Thorium levels in Monazite ~3 to 20%

Monazite sample containing 2 to 3% of thorium mixed with rare earths (from the Steenkampskraal mine, South Africa-Trevor Blench)

Fun Fact: Thorium for 1 GWe/yr

- Producing 1 GWe during one year will need 1.05 ton of thorium.
- 1 GW of thermal energy during one year requires only 0.453 ton of thorium.
- This is equivalent to 6,790 ton of thorium per year for the entire world power consumption of 15TW = 15×10^{12} W); this is based on average of 2 kW/person.
- Current world population is ~7.12 billion.
- Density of thorium = 11.7 g/cm^3, it takes a cube of thorium of a side a ≈ 34 cm to produce 1 GWth during one year.

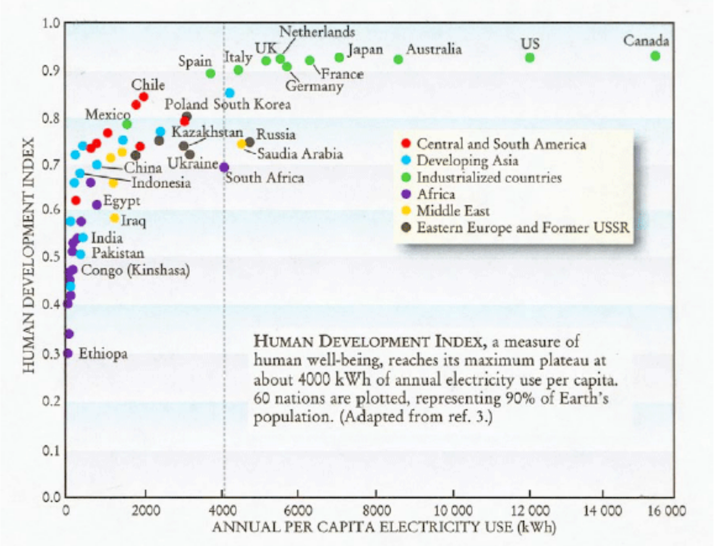
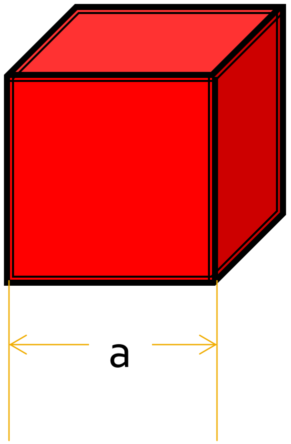


Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Livermore National Laboratory rep. no. UCRL-ID-140773.



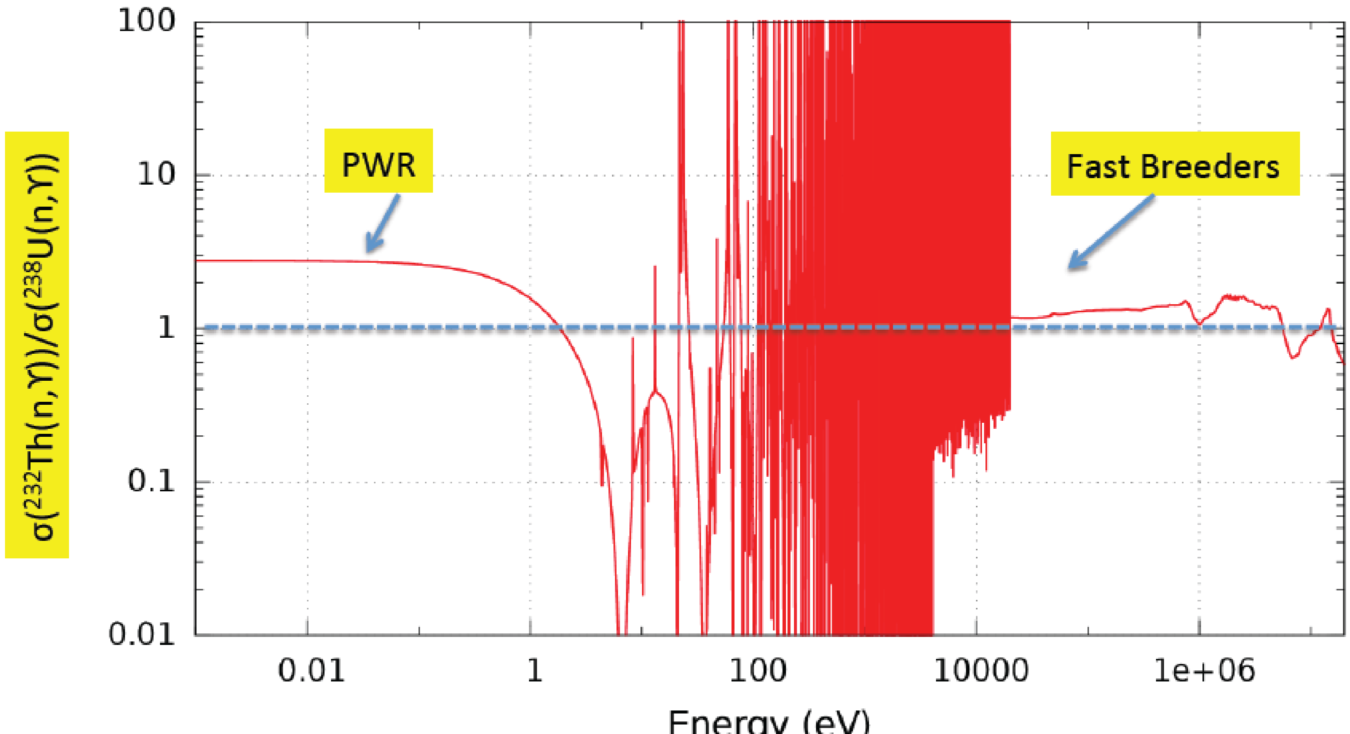
Why should we considered thorium-based fuel cycle?

- Increasing fissile resources by breeding U-233 from thorium.
- Improving fissile fuel utilization in thermal reactors.
- Significantly reducing U-235 enrichment requirements
- Decreasing production of plutonium and other transuranic (TRU) elements compared to the uranium fuel cycle.
- Advantageous neutronic and physical properties of thorium-based fuel (e.g., higher thermal conductivity, higher melting point, better behavior under irradiation, higher burn-up achievable).

Potential Disadvantage: Neutron Captures

- Thorium has a higher capture cross section than ^{238}U, and it takes longer to breed the fuel (^{233}U).

- ^{232}Th cannot be replaced ^{238}U right away in current reactors.



Experience of Thorium Use in Experimental and Power Reactors

VCU

- 1950-1970, great enthusiasm and regardless of the costs, a large number of possible avenues for energy production with thorium were investigated, not only in the US and USSR, but also in Europe and Asia.
- Thorium-based Elk River—Minnesota (1963) and Peach Bottom—Penn (1967) reactors were started only a few years after the 'founding fathers' of the two main reactor families of today, based on uranium fuel, PWR Shippingport—Penn (1957) and BWR Dresden– Illinois (1960).
- Breeder demonstration was performed at Shippingport in the late 1970s and early 1980s using a U-233/thorium cycle.
- This was the only US demonstration program using U-233 as the fissile seed material.
- Although this demonstration was successful, success was only achieved at the high cost of a sophisticated core design, and by sacrificing reactor performance.

Experience of Thorium Use in Experimental and Power Reactors

VCU

- Different high temperature reactor prototypes in USA, Germany and UK (the Dragon OECD-EURATOM project) have shown similar capacities with an excellent behavior at very high coolant temperatures (> 1000 °C).
- A molten salt reactor experiment has been operated rather successfully at Oak Ridge for some years.
- The separation of U-233 and thorium is usually done by wet liquid-liquid extraction using the THOREX process at Oak Ridge.
- Th and ThO2 dissolutions are not easy—additional hydrofluoric acid.
- U-233 with U-232 presents problems for fabrication, increasing processing cost.
- Reprocessed thorium also contains Th-228 ($t_{1/2}$ = 1.9 y) and Th-234 ($t_{1/2}$ = 24 d) preventing direct handling for some times.

Nuclear Reactors

Country	Name	Type	Power (MW)	Startup date	Fuel	Note
USA	Indian Point 1	PWR	265_e	1962	ThO_2–UO_2	Power includes 104 MWe from oil-fired superheater
	Elk River	BWR	22_e	1964	ThO_2–UO_2	Power includes 5 MWe from coal-fired superheater. Thorium loaded in the first core only
	Shippingport	PWR	60_e	1957	ThO_2–UO_2	Used both U-235 and plutonium as the initial fissile material. Successfully demonstrated thermal breeding using the 'seed/blanket' concept (Th/U-233)
	Peach Bottom	HTR	40_e	1967	ThC_2–UC_2	Coated particle fuel in prismatic graphite blocs – Th/HEU
	Fort St Vrain	HTR	330_e	1976	ThC_2–UC_2	Coated particle fuel in prismatic graphite blocs – Th/HEU
	MSRE	MSR	10_{th}	1965	ThF_4–UF_4	Operated with U-233 fuel since October 1968. No electricity production
UK	Dragon	HTR	20_{th}	1964	ThC_2–UC_2	Coated particle fuel. No electricity production. Many types of fuel irradiated
Germany	AVR	HTR	15_e	1967	ThC_2–UC_2	Coated particle fuel in pebbles. Maximum burn-up achieved: 150 GWd/t – TH/HEU
	THTR	HTR	300_e	1985	ThC_2–UC_2	Coated particle fuel in pebbles. Maximum burn-up achieved: 150 GWd/t – Th/HEU
	Lingen	BWR	60_e	1968	Th/Pu	Th/Pu was only loaded in some fuel test elements
India	Kakrapar (KAPS) 1–2	PHWR	200_e	1993/95	UO_2–ThO_2	Fuel: 19-element bundles. 500 kg of Th loaded
	Kaiga 1–2	PHWR	200_e	2000/03	UO_2–ThO_3	Fuel: 19-element bundles. Th is used only for power flattening
	Rajasthan (RAPS) 3–4	PHWR	200_e	2000	UO_2–ThO_4	Fuel: 19-element bundles. Th is used only for power flattening
	KAMINI	Neutron source	30 Kwe	–	U-233	Experimental reactor used for neutron radiography

Early Stimulants

- The initial push for thorium fuel development was to provide an alternative fuel cycle in response to the nuclear growth.
- Additional point is the abundance of thorium in comparison to uranium.
- By the mid-1970, the uranium price reached \$40/lb U_3O_8.
- The good in-core neutronic and physical behavior of thorium fuel under irradiation.
- A lower initial excess reactivity requirement (higher thermal conversion factor) of thorium-based cores using particular configurations.
- The feasibility of different types of reactors based on Th fuels has been successfully demonstrated.

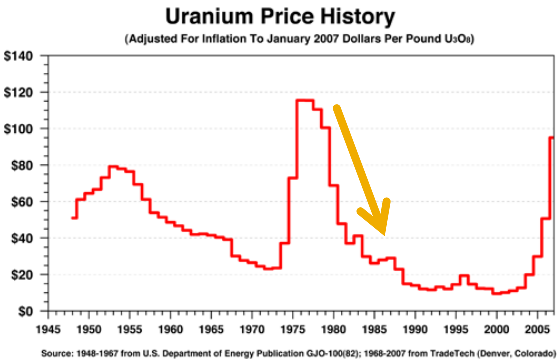
What factors killed These Stimulants?

VCU

- 1st Public Support:
  - Public support for nuclear power dramatically declined following the TMI in 1979.
  - Intensity amplified from Europe—Chernobyl, seven years later.

- 2nd U Price:
  - Starting from 1980s, $ value remained low for over two decades.
  - Nuclear weapon disarmament program (Megatons to Megawatts Program)—downblending.

- 3rd, the Ford and Carter Administration:
  - End to commercial reprocessing the US so that it no longer had the capability to recover the fissile material from any non-military used fuel.



Finally,...

- Proliferation concerns
  - The reference option for implementing the thorium cycle was to deploy it with highly enriched uranium (HEU).
  - Not only is HEU chemically separable from thorium (assuming seed and fertile material are combined), but some fuel designs completely separated the HEU driver fuel from the fertile thorium.

A Revival ...

- Development of a LWR proliferation-resistant fuel cycle (i.e. the Radkowsky Concept).
- Nuclear renaissance and resource scarcity that it might entail.
  - It was also stimulated by some of the same factors that were the main drivers for thorium cycle development in the 1950s and 1960s.
- The potential for a low production of plutonium and minor actinides in thorium based fuel cycles.
- Advanced reactor concepts based on thorium fuel cycles for future nuclear applications such as LWRs, HRs, Molten salt Reactors (MSRs), Accelerator-driven System (ADS).

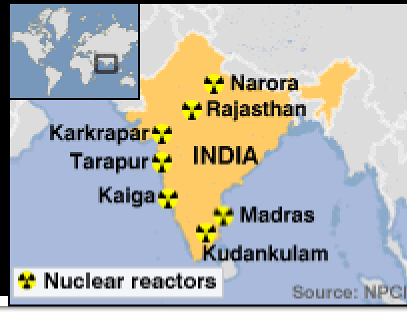
A Revival …

- Transmutation of minor actinides.
- Increase in price of uranium, which is closely tied to the perceived shortage of this material in light of a rapid growth of nuclear energy especially in Asian countries.
- Fukushima Accident.
- A new upswing of interest in thorium both within academic institutions and R&D organizations but more importantly by industry due to market conditions and new technologies.

Current Status in the World

- On going studies: USA, Russia, China, Canada, Sweden, Norway, Japan, France, and **India**.
- European Union—fostering R&D actions for the thorium cycle.
- International Atomic Energy Agency (IAEA) – reports regularly on this topic.
- Most programs – fundamental studies. Exception to India.

India …

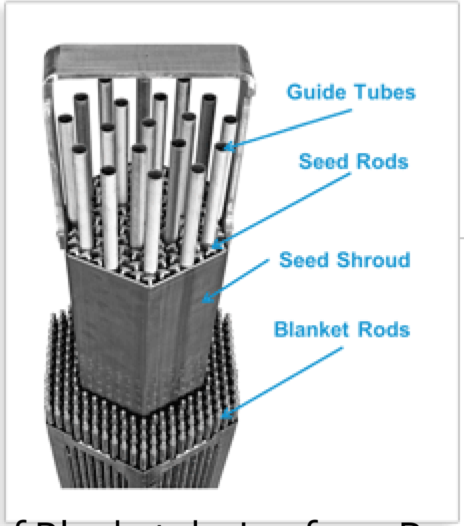


VCU

- Limited indigenous uranium resources (1% of the world's uranium resources).
- Difficulty in importing uranium because of political reasons.
- Six times more thorium than uranium.
- Utilization of thorium for large-scale energy production .

The Indian Strategy

- Due to small uranium resources, but the world #1 Thorium, India tries to incorporate it into front-end and back-end of the fuel cycle.
  - Use heavy water reactor (CANDU) or LWR to produce plutonium
  - Use Na cooled U-Pu fast reactors with a thorium blanket to breed ^{233}U
  - Reprocess blankets and manufacture 233U-Th fuel for advanced fast reactors or heavy water reactors.
- India still faces issues in complexity (three technologies), the sustainability and nuclear waste management.



Lightbridge's thorium-based seed and blanket assembly mockup for Russian-type VVER reactors used in thermal-hydraulic testing

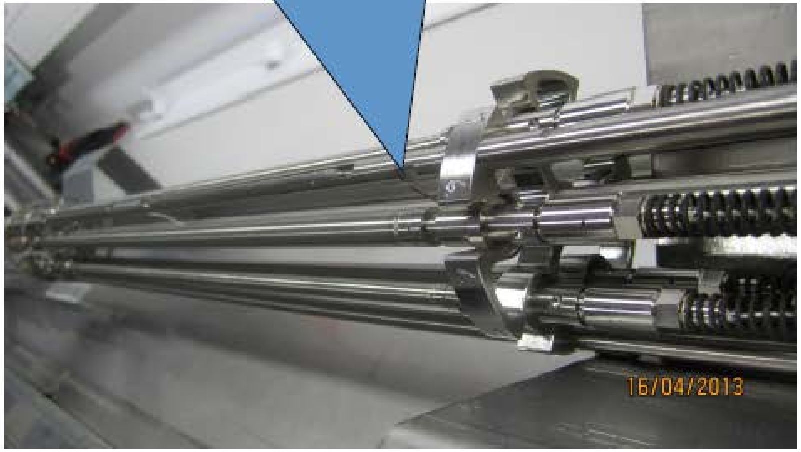
Example of Blanket design from Russian Voda Voda Energo Reactor

Recent Effort in LWR

Thor Energy (The Norwegian Thorium Initiative) collaborates with Westinghouse to carry out thorium fuel tests in the Halden research reactor.

APRIL 2013

- 2 Rods 85%Th - 15%Pu pellets, ITU, Germany
- 2 Rods 7%Th – 93%UOX, IFE, Norway
- 1 Rod 65%Th – 35%UOX, IFE, Norway
- 1 UOX Reference rod



Halden Research Reactor
Institute for Energy Technology (IFE)

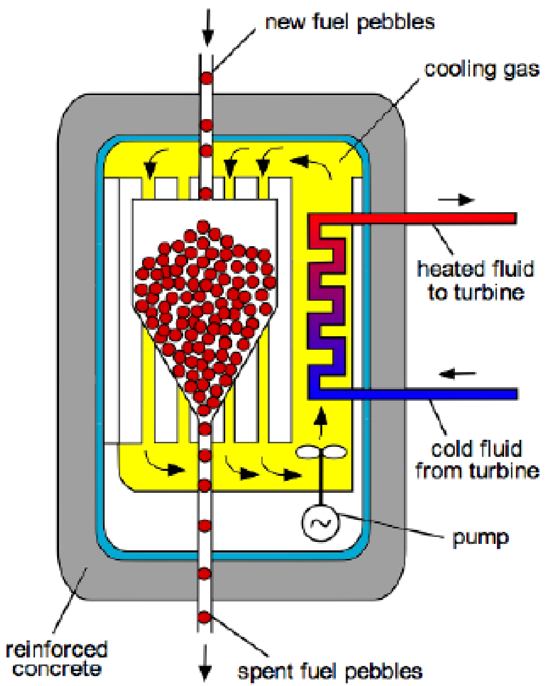
What are Other Studies?

- Use thorium blankets around reactors, to breed ^{233}U and introduce ^{233}U in fuel
  - (n + $^{232}Th \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$)
- Continuously move the fuel out for having fresh fuel
  - Pebble bed reactors (once through)
  - Molten salt reactors (reprocessing on-line)
- Accelerator Driven System (ADS), providing an external neutron source

Pebble Bed Critical Reactors

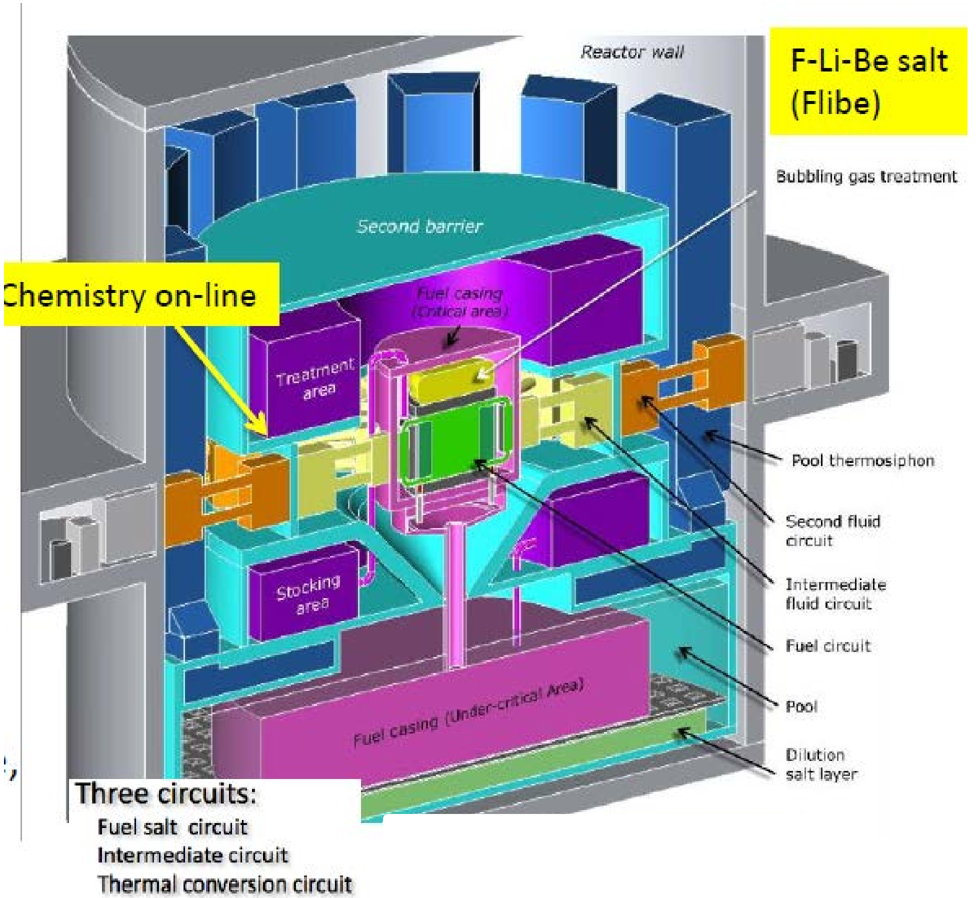
- Proposed by Farrington Daniels at Oakridge, in the 1940s. Initial developments in Germany (AVR Julich), followed by THTR-300MW (1983-1989). New developments in South Africa, now in the U.S. and Turkey
- Presented as passively safe, as high temperature systems can be cooled by natural air convection
- Several issues:
  - No containment building
  - Uses flammable graphite as moderator
  - Produces more high level nuclear waste than current nuclear reactor designs
  - Relies heavily on pebble integrity and fuel handling
  - Water ingress, hard for reprocessing

Pebble Bed Reactor scheme



Molten Salt Critical Reactors

- This is clearly a technology that is concentrating interest: China, India, UK, US, Czech Republic, France, Switzerland
- Pioneered at Oakridge in 1960 (MSRE, UF_4 – 7.4 MWth)
- Advantages
  - Liquid fuel, on-line reprocessing
  - High temperature (500 – 600 °C)
  - Passive cooling for decay heat removal
- Severe issues: neutron emission, online chemistry failure, corrosion, licensing
- Presently not using a fast neutron spectrum
- There is a well focused and most ambitious effort in China (Shanghai Institute of Applied Physics)



US-China Relation

The Chinese Academy of Sciences and U.S. Department of Energy Nuclear Energy Cooperation Memorandum of Understanding

MOU Executive Committee Co-Chairs
China – Mianheng Jiang (CAS) 江绵恒
U.S. – Peter Lyons (DOE)

Technical Coordination Co-Chairs
China – Zhiyuan Zhu (CAS) 朱志远
U.S. – Stephen Kung (DOE)

Nuclear Hybrid Energy Systems *
- Zhiyuan Zhu (CAS) 朱志远
  Yuhan Sun (SARI,CAS) 孙予罕
- Steven Aumeier (INL)

* Work scope governed by DOE-CAS Science Protocol Agreement

Molten Salt Coolant Systems
- Hongjie Xu (SINAP, CAS) 徐洪杰
  Weiguang Huang (SARI,CAS) 黄伟光
- Cecil Parks (ORNL)
  Charles Forsberg (MIT)

Nuclear Fuel Resources
- Zhimin Dai (SINAP, CAS) 戴志敏
  Biao Jiang (SARI,CAS) 姜标
- Phil Britt (ORNL)
  John Arnold (UC-Berkeley)

SINAP: Shanghai Institute of Applied Physics
SARI: Shanghai Advanced Research Institute
ORNL: Oak Ridge National Laboratory
INL: Idaho National Laboratory
MIT: Massachusetts Institute of Technology
UC-Berkeley: University of California at Berkeley

Efforts have been made and the Chinese Government decided that the first fully-functioning thorium MSR reactor should be built within **ten years**, instead of 25 years as originally planned.

Chinese Commitment in Th-MSR

IThEO.org
International Thorium Energy Organisation

China Announces Thorium Energy Project

1 February, 2011

The Chinese Academy of Sciences announced that it will finance the development of a programme to develop a Thorium Fuelled Molten Salt Reactor (TFMSR). This is first of four "strategic leader in science and technology projects" that the Chinese Academy of Science will be supporting.

The Head of the Chinese TFMSR programme is Dr Jiang Mianheng, Graduate of Drexel University, with a PhD in electrical engineering. His father Jiang Zemin, was the former President of the People's Republic of China from 1993 to 2003. This gives an indication of the importance the Chinese Leadership attach to the TFMSR programme.

This is a clear and important endorsement of the benefits of the TFMSR's namely:

- Excellent nuclear and passive safety features,
- Greatly improved proliferation resistance,
- Significantly reduced high active waste production,
- Excellent resource utilisation as a result of the very high burn-up achieved,
- Overall economics that offer the prospect of being competitive with coal.

This is Dr. Jiang Mianheng, who is leading the Chinese thorium MSR project in the Chinese Academy of Sciences. Dr. Jiang is a graduate of Drexel University with a PhD in electrical engineering. His father is Jiang Zemin, former president of the People's Republic of China from 1993 to 2003. He most recently toured Oak Ridge National Lab Fall of 2010 to see MSR.

Th-MSR versus LWRs

Th-MSR Technology can be	Traditional LWRs are
1. Economically and commercially viable	1. Not economically viable without massive government support, subsidies and the transfer of cost and risks to the public
2. Constructed on assembly line	
3. Model-design permitting & Modular	

Th-MSR Technology will NOT	Traditional LWRs CAN & DO
1. Blow up	1. Blow up
2. Melt down	2. Melt down
3. Cause widespread radiation	3. Cause widespread radiation

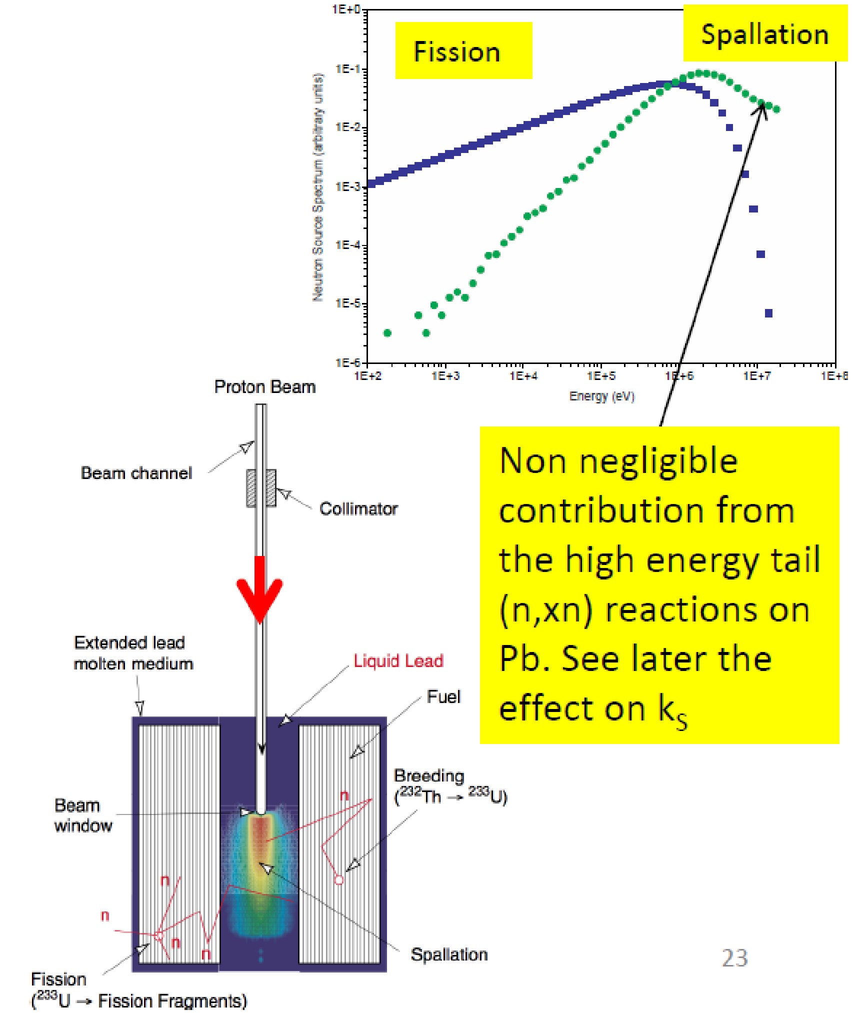
Th-MSR will help to eliminate the nuclear waste/used fuel issue! IS IT TRUE?

Other Key Factors

Th-MSR Advantages	LWR Disadvantages
1. Th-MSRs utilize nearly 100% of the available energy from the fuel-thus reducing nuclear waste/used fuel issues	1. LWRs (traditional design) use a fraction of available energy from its fuel—resulting in large amount of nuclear waste/used fuel issues
2. Safely operate at +700 °C	2. Operate at about 350 °C
3. Fuel/coolant is not under pressure	3. Coolant is under tremendous pressure
4. 100% passive safety	4. 100% mechanical safety
5. Low capital expenditure?	5. High capital expenditure?

ADS – ρ < 1 Approach

- A particle accelerator providing a neutron source
- A core in which both source neutrons and fission neutrons are working—restricted here to the case of a moderator allowing for a fast neutron spectrum
- Physics (Neutron production by spallation from the beam and Neutron transport and interaction in the core)
- Physics with other ADS elements (Cooling and Electric power production efficiency

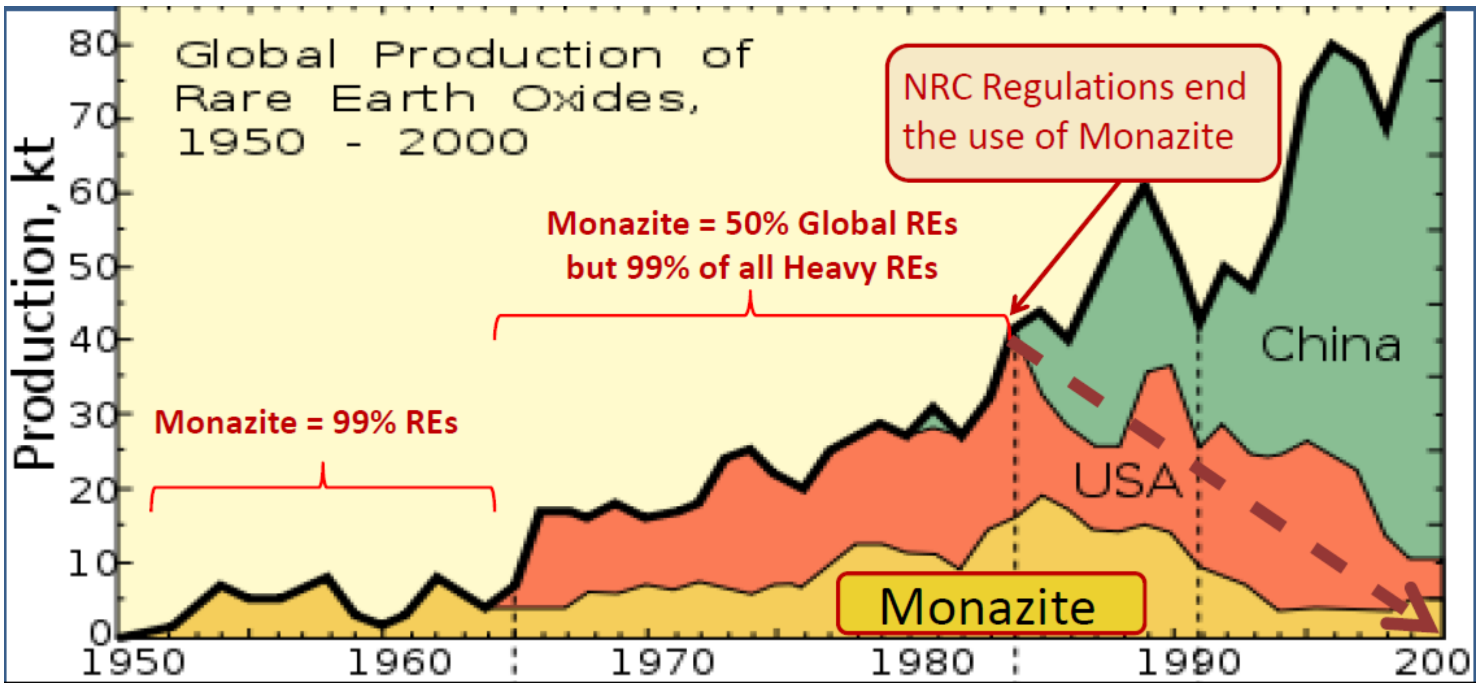


Key Features – Front-End

- Mining and Milling
  - No thorium-based fuel in industrial or commercial scale→ no international market
  - Thorium is currently being used for special metal alloys with magnesium, coating tungsten wire filaments for electronic equipment, high refractive glasses and catalyst for chemical industry, and medical applications

Key Features – Front-End

- The NRC & IAEA set the threshold classification of SOURCE MATERIAL to 0.05%→ Ended the use of Monazite by all 'western's rare earth producers.

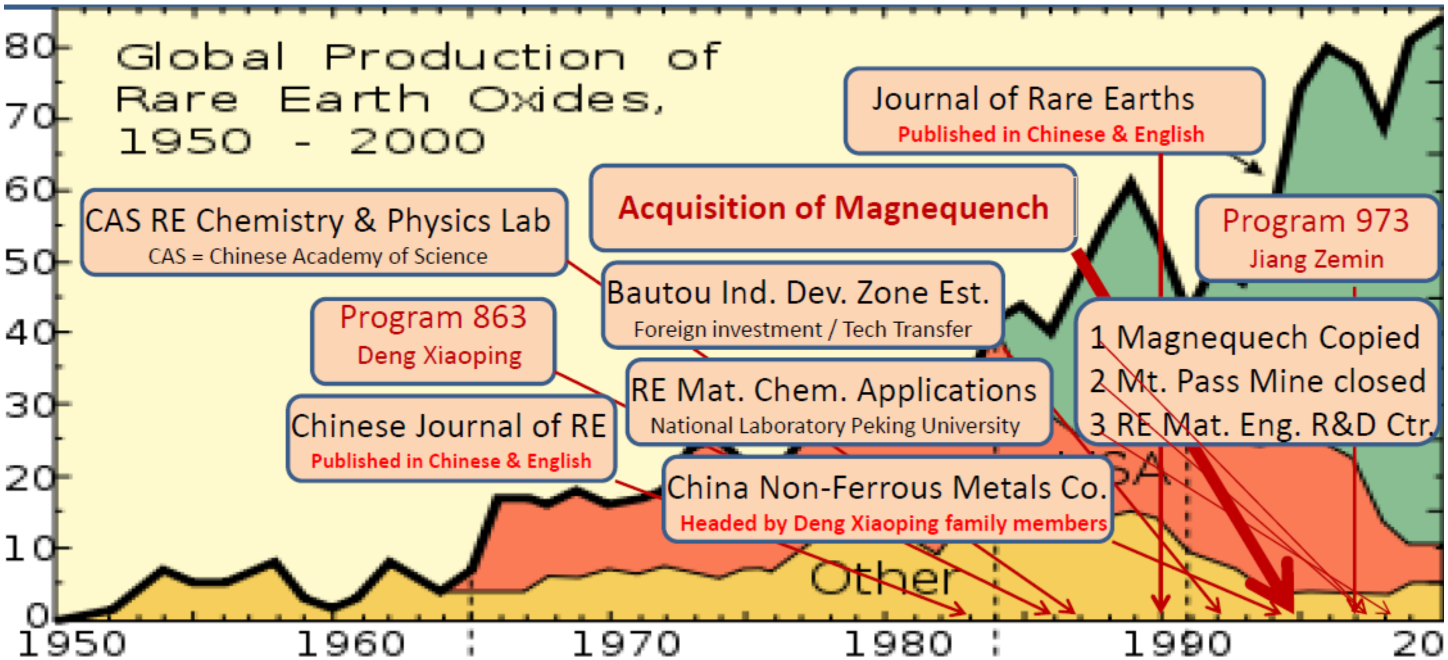


- Growth in Chinese production!

Ref: [11]

Key Features – Front-End

- Highest Chinese government controls the Rare Earth industry, including government funded programs.
- All programs were part of the public record.
- The U.S. ignores this ongoing situation, with Congress approving key technology transfers!



Ref: [11]

Key Features – Thermal Reactors

- Low capture X-section of U-233 compared to U-235 and Pu-239 makes this an advantageous feature.

- However, this beneficial is countered by:
  - Losses of neutrons in Pa-233
  - Relatively higher neutron capture X-section of Th-232 in comparison to U-238.

	U-233	U-235	Pu-239
Cross-section (barns)			
Fission			
(1) 2200 m/sec value	527	579	741
(2) Resonance integral	764	275	301
Capture			
(1) 2200 m/sec value	54	100	267
(2) Resonance integral	140	144	200
Neutron/fission (on average)	2.5	2.4	2.9
Eta (1)	2.27	2.04	2.12
Eta (2)	2.11	1.56	1.74

  - Contribution to fission by the build up of higher isotopes resulting from neutron captures starting from U-233, is less useful for energy production than the equivalent process starting from plutonium.

Key Features – Fast Reactors

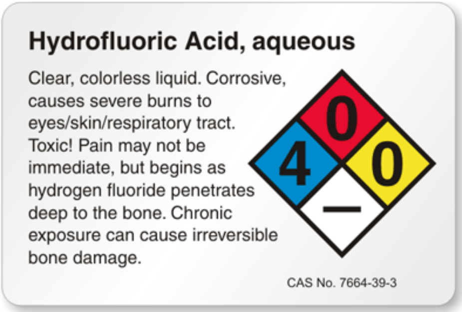
- The fission X-section of U-233 is considerably higher than the corresponding data for U-235 and Pu-239, and the capture X-section is lower.

	U-233	U-235	Pu-239
Cross-section (barns)			
Fission	2.8	2.0	1.9
Capture	0.3	0.5	0.6
Neutron/fission (on average)	2.5	2.5	2.9
Eta	2.26	2.0	2.20

- U-233 appears to be attractive, however, the overall production of new fuel compared with fuel consumption depends on contributions to the neutron balance from other sources.
- This is offset by the low fission contribution from the fertile Th-232 isotope as compared with the much larger contribution from U-238 in fuel cycles.
- Th-232/U-233 fuel cycle proves to be relatively unattractive and fast reactors studies suggest that thorium cycle would give about 20% less bred fissile material than a U-238/plutonium cycle on a reasonably comparable basis.

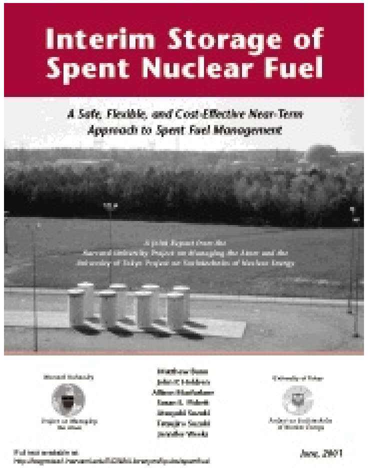
Key Features/Problems—Back-End

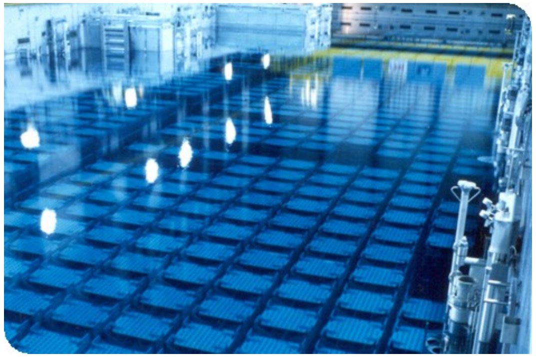
- Reprocessing
  - Idea is to retrieve the fissile U-233.
  - Developed by ORNL, THOREX is a hydrometallurgical process.
  - Additional of hydrofluoric acid is necessary to improve the dissolution process, creating further corrosion issues.
  - Aluminum nitrate is added as a buffer increasing waste production.
  - THOREX has 50%-70% more vitrified waste than PUREX.
  - High temperature is required.
  - Recent interest in pyroprocessing technology(electrochemical separation) using molten salt technology.



Key Features/Problems—Back-End

- Interim Storage and Waste Disposal
  - High burn ups help reducing number of fuel assemblies.
  - Less problematic than uranium because of the relative chemical inertness of thorium.
  - Fuel oxidation is unlikely to be a concern during dry storage.
  - ThO_2 is chemically stable and almost insoluble in ground water (U can be converted into the water-soluble uranyl cation UO_2^{2+}).
  - Still produce radionuclides such as Pa-231, Th-229 and U-230 which have a long term radiological impact.
  - But it is still less than for the standard U-Pu cycle for the same energy output.





Summary

- Thorium is NOT a direct competitor to uranium.
- Thorium is an attractive fuel cycle option for future development of nuclear energy:
  - The enhancement of fuel resources by producing a new fissile isotope, U-233 (best for thermal neutrons).
  - The abundance in many countries.
  - The good in-core neutronic and physical behavior allowing to reach high burn-ups, high conversion factors compared to U-233 and even breeding in **thermal reactors**.
  - It reduces the global inventory of long-lived minor actinides → reducing waste and storage issue.
  - It will allows very efficient plutonium burning.

Original motivations

New aspects

Summary

- Successful Experience
  - Gained knowledge from both test reactors and power reactors had been accomplished.
  - Feasibility of the front-end fuel cycle technologies (mining, fuel fabrication) has been successfully demonstrated with generally rather old technologies.
  - MOX fuel development has been accomplished.

Summary

- Challenges
  - Practical experience in the back-end of fuel cycle is lacking.
  - Development of a large scale infrastructure is necessary for mining milling, fuel fabrication, transport and reprocessing of thorium-based fuel.
  - To recover U-233, further fundamental studies are necessary in reprocessing.
  - Shielded facility is necessary due to U-232 and its daughters.

SUMMING UP

90 232.04 Th Thorium

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- Thorium-based fuel shows useful characteristics.
- However, it does not appear sufficient to justify an industrial development in the short-term.
- Its potential advantages are overshadowed by some real drawbacks.
- In future, it has a potential in lower the radiotoxicity of radioactive waste to be disposed and, if U-233 is recycled, could reduce demand for uranium.
- The possibility of achieving near breeding or even breeding conditions in thermal reactors yields an attractive feature of the thorium cycle.

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