The Thorium Fuel Cycle and Waste Management

"What? Give up just as we are on the verge of success? Never!"

—Prof. Hardwigg in "Journey to the Center of the Earth" by Jules Verne.

About Thorium

The thorium fuel cycle is a potential alternative to the uranium fuel cycle.

Thorium discovered by the Swedish chemist Jacob Berzelium in 1828.

Named after the Norse god Thor.

There are 32 known isotopes of Th and all are radioactive.

99.98% of all thorium occurs as ^{232}Th.

Thorium characteristics

Thorium first decays to ^{228}Ra by alpha decay. Half life = 14.1 x 10^{10} (billion) years.

There is about 3 to 5 times more thorium in nature than uranium.

World's reserve of Th is about 6,335,000 tonnes.

India (13% of the total), Brazil (10%), Australia and the U.S.(9%), and Egypt (6%).

Sources of thorium

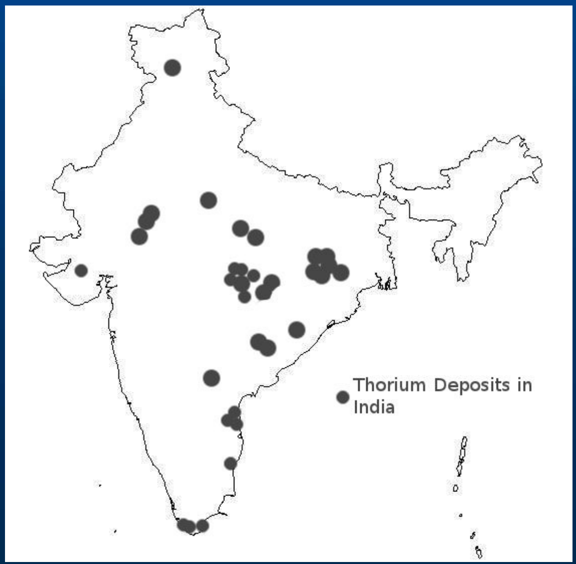
The primary source of thorium is a phosphate mineral called monazite ((cerium, lanthanum, neodymium, thorium) (PO_4, SiO_2)).

A minor source is thorianite → (ThO_2)

Thorium sources

Monazite forms in igneous rocks such as in granite, and deposits may occur as a placer deposit (natural accumulation from the weathering of the source rocks).

India and China are currently the major producers of monazite. The U.S. does not mine the mineral.



Thorium as a fuel

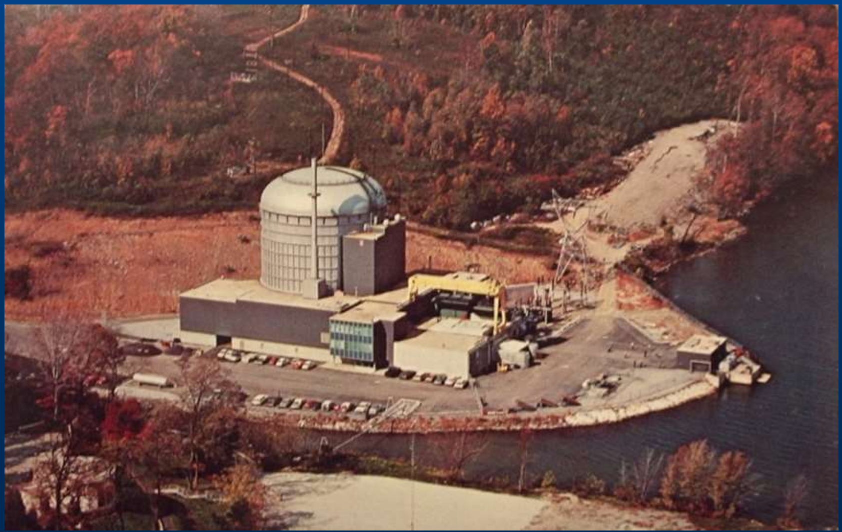
During the 1960s and 1970s, research was conducted on the use of thorium in reactors in the U.S., U.K., Japan, Russia, and France but phased out in about 1980—except in India where there is an active research program today.

Several experimental reactors were tested such as the Peach Bottom Unit 1 reactor in Pennsylvania.

Peach Bottom Unit 1

Peach Bottom Unit 1 (110 megawatts) operated from 1967 to 1974. It was a high-temperature, helium-cooled, graphite-moderated design. It used as fuel microspheres made of a mixture of thorium and uranium carbide in a graphite matrix.

($^{235}U + ThO_2$). Why not just thorium?



Transmuting thorium

Like ^{238}U, ^{232}Th is not fissile: it cannot sustain a chain reaction. It is said to be "fertile."

It can be transmuted into ^{233}U which can be used as a reactor fuel when it absorbs a neutron:

$^{232}Th + \eta \rightarrow {}^{233}Th \rightarrow {}^{233}Pa + e^{-} + \bar{\upsilon}$, then

$^{233}Pa \rightarrow e^{-} + \bar{\upsilon} + {}^{233}U$

where Pa = protactinium, and $\bar{\upsilon}$ is a anti-neutrino. ^{233}Pa has a half-life of 27.0 days.

But what is the next step?

One of the major advantages of using thorium is that we do not create plutonium when compared with using ^{235}U. Described as both a strength and a weakness.

If we ignore the source of the neutrons as a short-coming, we could, in theory, breed ^{233}U from thorium, then chemically extract (reprocess) the “new”uranium for use in a reactor.

Thorex

The Thorex process is being developed in India. Irradiated thoria (ThO_2) is, however, resistant to chemical dissolution. The first step is to store the thoria containing ^{233}U to allow for the decay of ^{233}Pa (half-life of 27 days).

Then the thoria pellets are chopped up and placed in 13 M HNO_3 + 0.04 M HF + 0.1 M $Al(NO_3)_3$.

Thorex

Tributyl phosphate (TBP) + n-dodecane is then used to extract the ^{233}U:

$$^{233}UO_2^{2+} + 2TBP + 2NO_3^- \leftrightharpoons {}^{233}UO_2(NO_3)_2 \cdot 2TBP$$

Some thorium (as Th^{4+}) is co-extracted, but can be removed from the organic phase by adding 1 to 2 M HNO_3, then separating the aqueous phase from the organic phase a second time.

Undesirable side reaction

In addition to ^{233}U, ^{232}Th also transmutes into ^{232}U.

^{233}U and ^{232}U cannot be chemically separated.

^{232}U decays into some "hard gamma emitters" (2 to 2.6 MeV) by alpha decay:

$$^{232}U \rightarrow {}^{228}Th \rightarrow {}^{224}Ra \rightarrow {}^{220}Rn \rightarrow {}^{216}Po \rightarrow {}^{212}Pb \ldots$$

68.9 y 1.91 y 3.6 d 56 s 0.15 s 10.6 h

Specific activities of three ^{232}U decay products

^{224}Ra	160,000 Ci/g
^{220}Ra	930,000,000 Ci/g
^{212}Pb	1,400,000 Ci/g
^{233}U	0.0098 Ci/g
^{235}U	2.2×10^{-6} Ci/g
^{242}Pu	0.004 Ci/g

Because of these high-activity decay products from ^{232}U which will be co-extracted with ^{233}U, any commercial-scale application of Thorex will require remote handling and/or shielding.

Fissile Drivers

Thorium-based fuels have, however, evolved in a different direction. Of the 14 experimental reactors that have been tested since 1960 in 6 countries, the thorium was combined with a fissile "driver" such as ^{233}U, ^{235}U, and plutonium.

Recall Peach Bottom Unit 1: it used as fuel microspheres made thorium and (93% enriched) uranium in a graphite matrix

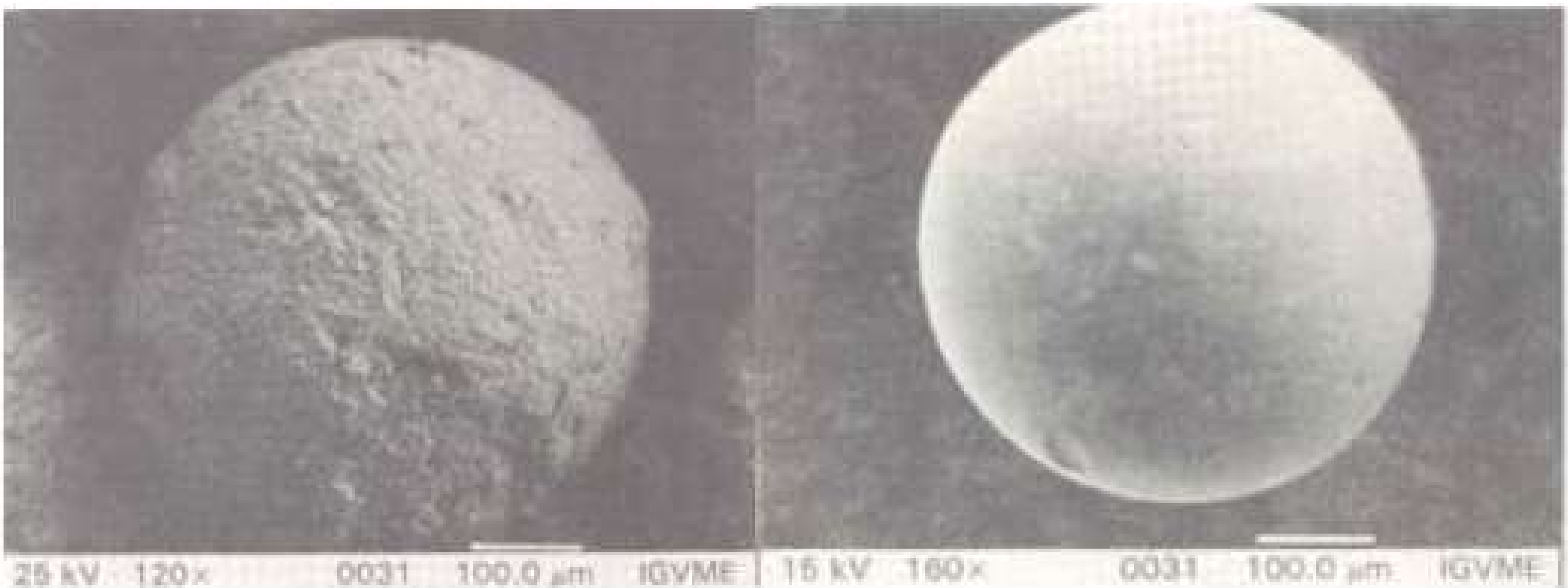


Fig. 20. Microstructure of sintered (Th,U)O_2 pellets prepared from (a) 'porous' and (b) 'non-porous' microspheres.

Spent fuel from PB Unit 1

The spent fuel was stored in a pool, then sent to the Idaho National Engineering Lab. The facility is currently in SAFSTOR, and final decommissioning will take place in 2034.

While this spent fuel may not be representative of that produced in commercial applications in the future, compositional data will yield insights on the early waste product.

Core 2 composition (from Morissett et al., 1986)

^{232}Th	92%	Residual fuel component
^{235}U	5.3%	Residual fuel component
^{233}U	2.0%	Product of thorium transmutation
^{234}U	0.36%	Decay product of ^{238}U
^{237}Np	0.13%	Decay product of ^{237}U
^{233}Pa	0.02%	Decay product from ^{233}Th
^{239}Pu	157 mg/kg	Fission product of ^{238}U
^{242}Pu	42 mg/kg	Fission product
^{232}U	6 mg/kg	Product of thorium transmutation
^{231}Pa	5 mg/kg	Decay product of ^{231}Th

Composition of “spent thorium-based fuel” (Zabunoglu and Albas, 2003).

Thorium	84.4%
Uranium	5.41%
Neptunium	0.14%
Plutonium	0.11 %
Protactinium	45.7 mg/kg
Americium	2.19 mg/kg
Curium	0.95 mg/kg

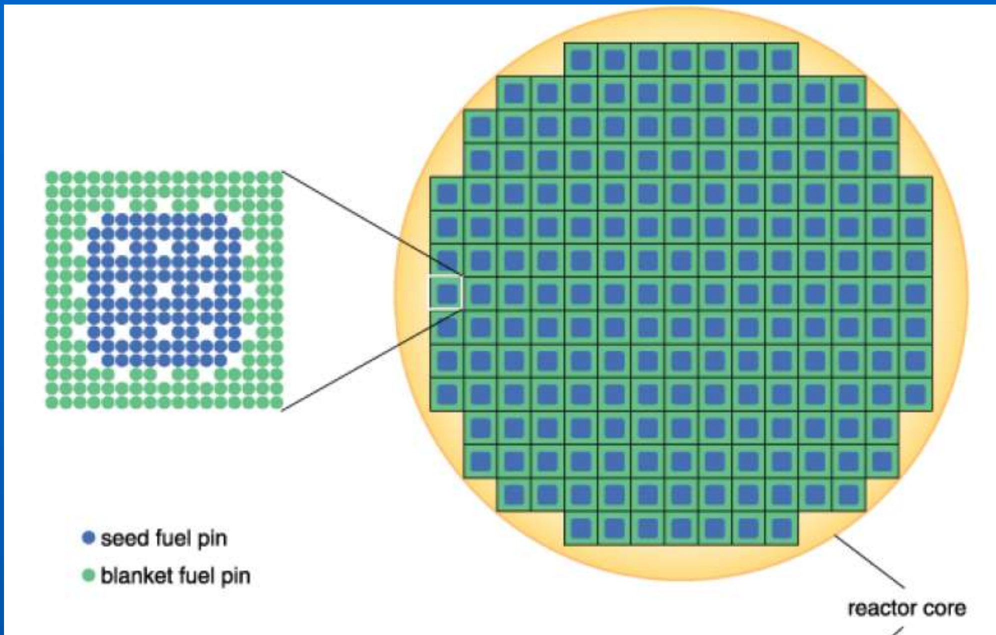
The seed-blanket fuel design

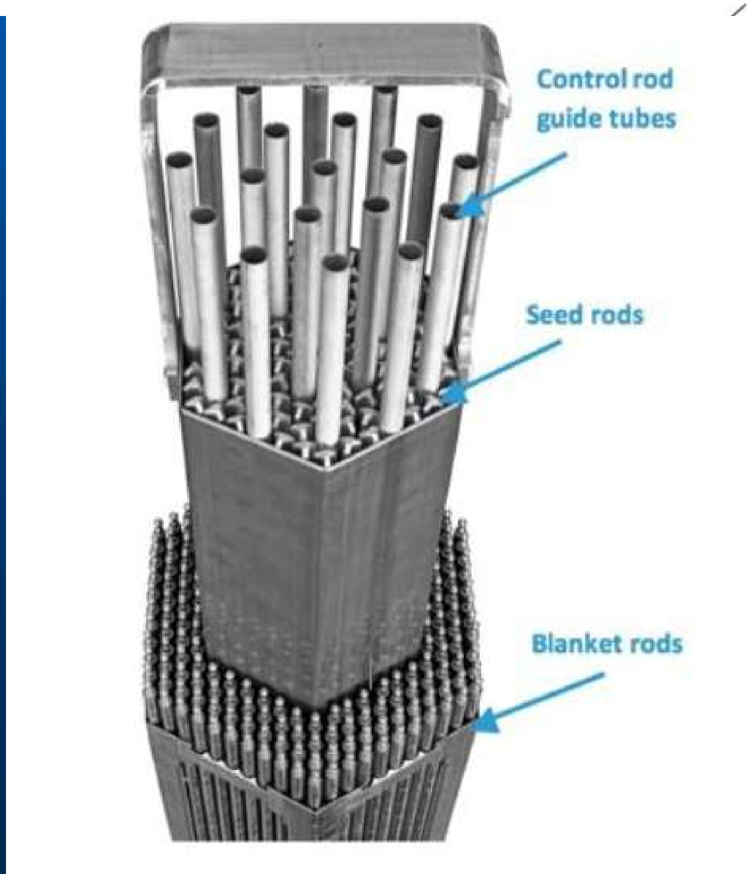
The seed-blanket fuel design is a once-though, light-water technology now called the Radkowsky Thorium Fuel after Alvin Radkowsky (1915-2002).

Seed = ^{235}U, ^{233}U, Pu, or

MOX fuel.

Blanket = Th or ThO_2





There is a Fast Breeder Test Reactor (40 Megwatt) operating in India since 1985 that uses thorium-plutonium and thorium-^{233}U blankets.

Summary about thorium

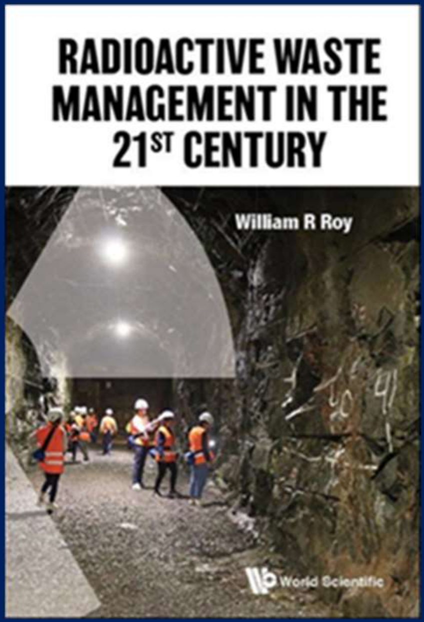
Advantages	Disadvantages
1. Thorium is more abundant than uranium in nature.	6. Thorium is not fissile: it cannot sustain a chain reaction.
2. Thorium-containing minerals (primarily monzanite) are more easily mined in many countries than uranium.	7. Thorium must be transmuted into ^{233}U to be used as a fissile fuel.
3. Thorium has the potential to supplement the supply of uranium.	8. Uranium-233 must be extracted from irradiated thorium-232.
4. In the ^{232}Th-^{233}U fuel cycle, plutonium is not produced, and fewer actinides are created.	9. Thorium-232 will need to be mixed with a "driver" such as ^{233}U, ^{235}U or ^{239}Pu.
5. The presence of ^{232}U could create desirable non-proliferation properties.	10. Because of the presence of ^{232}U, thorium-based fuels may need to be processed remotely in a shielded environment.
	11. Thorium-based fuels are currently more expensive than uranium-based fuels.
	12. Other than in India, there is little global interest to develop thorium-based fuels, and experiences have been negative and limited.

What can we expect?

The disposal of spent blanket would pose fewer concerns (than uranium-based fuels) because of the absence of plutonium and the reduced amounts of Am, Cm, and Np. The presence of ^{231}Pa (half-live of 32,500 years), ^{229}Th (97,000), and ^{230}Th (75,400 years), complicates the picture. ANS: the wastes created by the thorium fuel cycle "would still require the creation of geological repositories."

Class Assignment 4

Read Chapter 3.



Questions?