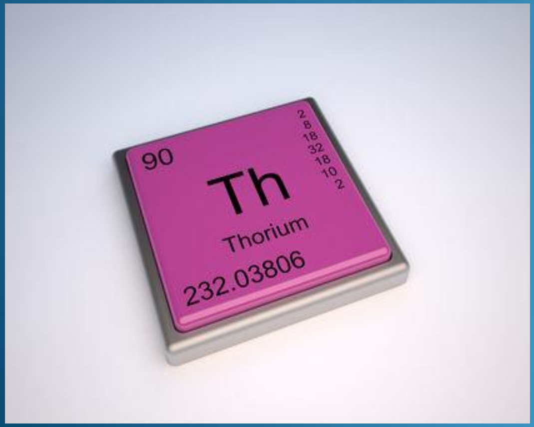
The Thorium Fuel Cycle : past achievements & future prospects



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Contents

- ***General considerations***
  - Why, How, How much …
- Thorium in reactors
  - Advantages/Drawbacks, uranium savings
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Thorium is an old story….

- The use of thorium was considered as an option for the fuel of nuclear reactors since the birth of nuclear energy.

- "New Pile Committee" created in April 1944 in the USA(1) to explore a variety of reactor concepts did recommend that "more work should be done on the nuclear development of thorium because of its greater availability"

- This Committee also suggested experiments to develop reactors that would convert thorium to uranium-233

(1) : With 3 Nobel prize : E. Wigner, E. Fermi, J. Franck

What was written in 1966

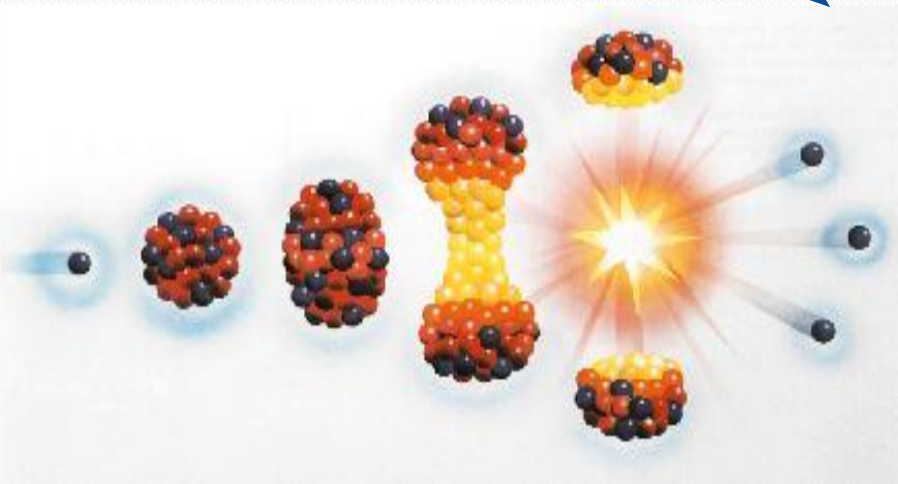
Preface of the

« Proceeding of the second international thorium fuel cycle symposium Gatlinburg, Tennessee – May 3-6, 1966 – US/AEC" ***(833 pages)***

During the time since the first Thorium Fuel Cycle Symposium was held (December 1962), four reactors based on the thorium fuel cycle have become operational, new estimates suggesting even more extensive deposits of low-cost thorium ores than were previously thought to exist have been made, improved methods for preparing and for fabricating thorium fuel materials have been developed, and studies for processing them have been carried out. It is time to take a fresh look at the reasons for working on the thorium fuel cycle and at its long-range prospects. This symposium was designed to that end. Its international flavor attests to the widespread interest in thorium. The nature of the papers clearly shows that the interest is not merely dilettante but is an expression of confidence in the thorium fuel cycle to produce economically competitive power.

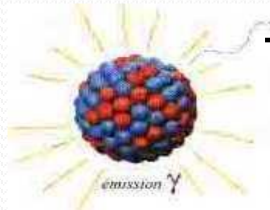
Why thorium ?

Th 232 + n → *Th233/Pa233* → **U 233**



Energy

A reminder : the "reproduction factor" η



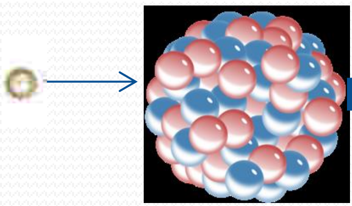
The excess energy of the nucleus is released through gamma rays emissions

(for U233 this leads to the formation of U234)

Absorption of a neutron by a fissile nucleus

8 % of the cases (U233)

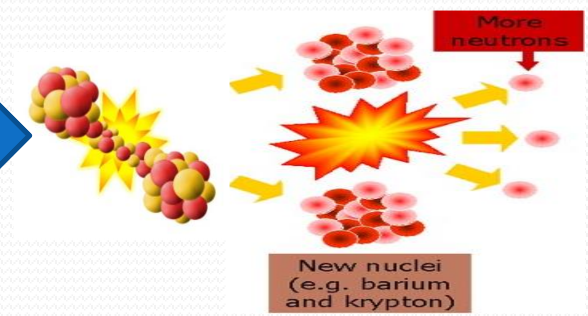
15 % for U235



The nucleus is a highly excited state

92 % of the cases (U233)

85 % for U235



The fission of the nucleus releases several neutrons (ʋ)

For U233, ʋ = 2,498 and thus the number of neutrons "recovered" from ONE neutron absorbed the nucleus is η = 2,498 * 0,92 = 2,297

(only 2,085 for U235)

U 233 is the BEST FISSILE isotope in for "THERMAL" neutrons (v = 2200 m/s)

	U 233	U 235	Pu 239
η in thermal energy range	**2.29**	2.07	2.11
η in fast energy range	2.27	1.88	2.33

To « breed », η must be greater than 2 (η - 2 > 0):

- ➔ one neutron needed to sustain the chain reaction and
- ➔ another one needed to make a new fissile nucleus

η – 2 = 0,29 for U 233 and only 0,07 for U 235 , thus …

Even <u>thermal breeding</u> can be achieved with Th-U233 system

➔Much less fissile inventory needed in a thermal reactor (at least a factor 5)

BUT ……

Thorium is NOT a substitute to natural uranium (Unat) :

One can sustain a chain reaction with Unat

with thorium, one CANNOT

Thorium occurrence in nature

- Thorium : fairly evenly spread around earth.

Thorium metal *(10,96 g/cm³)*

- The chief mineral hosts for thorium are monazite[(1)], carbonatite and thorite

Natural abundance of thorium compared to uranium

	Uranium (U)	Thorium (Th)	Th / U
Solar system (average, ppm)	$0.294 * 10^{-6}$	$1.09 * 10^{-6}$	0.27
Earth crust (average, ppm)	2.7	9.6	3.5
Sea water (average, ppm)	0.0033	< 0,00001	< 0,01

World « reserves »: at least several millions tons

(≥ uranium)

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How to use thorium in a reactor ?

- Thorium MUST be MIXED with a FISSSILE material
- There are 4 main possible “combinations” (= 4 main “fuel cycles”) :
  - U 235 : Th/HEU cycle (excluded today ➔ proliferation)
  - ***Plutonium : Th/Pu cycle (= MOX)***
  - U233 : Th/U233 cycle (but stocks of U233 must be available)
  - 20 % enriched U : Th/MEU cycle (« Radkowski » thorium concept)

Nuclear reactors having used thorium

- The pioneers (USA)
  - Shippingport : PWR, 60 MWe (1957)

    → **Th/U233 breeder was demonstrated in the late 1970s**
  - Elk river : BWR, 22 MWe (1963)
  - **MSRE : Molten Salt Reactor Experiment (Oak Ridge) in the 60's**

- The use of thorium in HTRs
  - USA (Prismatic blocs) : Peach Bottom (40 MWe, 1967) and FSV (330 MWe, 1976)
  - Germany (pebble bed core) : AVR (15 MWe, 1967) and THTR (300 MWe, 1985)

- The use of thorium in India

  Partly used in some PHWRs but India plans to use it in an extensive way in its future nuclear program

Thorium in nuclear reactors : available results (1/2)

- In addition to the demonstrations of use the of thorium realized in the past in various reactors, numerous studies have been carried out to assess the performances of thorium cycles in all kinds of reactors (LWRs, HTRs, MSRs, FNRs, HWRs, etc.)

- Some general tendencies can be drawn from these available results :

  - The use of thorium in conventional thermal reactors does not lead to significant Unat savings (typical conversion ratios, CR, < 0,7)

  - If "near breeding" (CR close to 1) can be achieved in thermal reactors, uranium savings become very significant. HTR's and **HWR**'s (and Gen-IV **MSR**) could be particularly suited to reach such high conversion ratios because of their very good neutron economy.

Thorium in nuclear reactors : available results (2/2)

- **Breeding conditions (CR>1) can be achieved in thermal reactors** with Th/U233 fuels (Shippingport demonstration, MSR studies). However, it is at the price of technological tricks which seem very challenging for commercial reactors.

- There is no incentive to use thorium in FBRs because U233 presents less good nuclear properties than Pu, and Th is much less fissile than U238 for fast neutrons (+more captures). Anyhow, should FBRs be deployed, there would be largely enough U for a sustainable nuclear energy development.

Main advantages and drawbacks of thorium in reactors (1/2)

- ***Drawbacks :***
  - Potential high concentration of Pa-233 which « robs » neutrons [(1)] and which increase reactivity after shutdown (Pa233➔ U233)
  - For Fast neutrons (only) : Less breeding performances than U/Pu
  - Less Doppler coefficient (but still negative!)
  - Higher fissile “commitment” at the beginning of life of reactors because of relative higher capture of thorium compared to U238
  - More gaseous fission products for U233 than for U235

(1) With a capture cross section $\sigma = 40 \times 10^{-24}$ cm2 for Pa233 and a disintegration constant $\lambda = 2{,}97 \times 10^{-7}$ sec–1 (corresponding to $T_{1/2} = 27$ days), the ratio between capture rate of Pa233 and its decay rate is, for a neutron flux φ (in n/cm2 · sec) , equal to 1,35 × 10–16 φ. Thus, this ratio become relatively significant (> 1%) for $\varphi > 10^{14}$ n/cm2 · sec.

Main advantages and drawbacks of thorium in reactors (2/2)

- ***Advantages : (compared to U)***
  - **High melting point** (ThO_2 : 3300°C, UO_2 : 2800°C)
  - **High chemical stability** and high FP retention in of ThO2 matrix
  - Better characteristics for power distribution, lower reactivity loss along fuel depletion (U233), **LESS CAPTURING F.P**. (➔less Xe and Sm effects, better neutron “economy”,…)
  - Better behavior under irradiation ➔ **higher burnup**
  - More **favorable safety characteristics** :
    - Overall temperature coefficient (moderator, spectrum shift)
    - Less chemical reactivity with water et vapor
    - Void coefficient much more favorable in FNR/Na

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Challenges for thorium cycle industrial development (1/3)

- **Mining**

  - Large efforts of thorium ore prospection would be needed (but in the long term, if thorium cycle is developed at a large scale)
  - External irradiation is much higher than in the uranium case before Th232 purification step (because of Tl-208)
  - However, mining of open pit monazite deposits (presently the main source of thorium) is easier than that of most uranium bearing ores
  - Management of thorium mine tailings is also simpler than in the case of uranium mainly because of the much shorter half live of « thoron » (= Rn 220 : 55 sec) than of radon (Rn 222 : 8 days, daughter of Ra 226, 1600 years)
  - Preparation of thorium, similar to that of rare earths, entails its separation from many other (valuable) compounds, hence, it is not too straightforward (many manipulations and chemical steps)

Challenges for thorium cycle industrial development (2/3)

- **Fuel manufacture**

  - Small scale industrial experiences exists : PWRs (Elk River, indian point 1, Shippingport), HTRs (US, Germany), PHWRs and LMFBRs (India)

ThO2 fuel pellets (BARC facility in India)

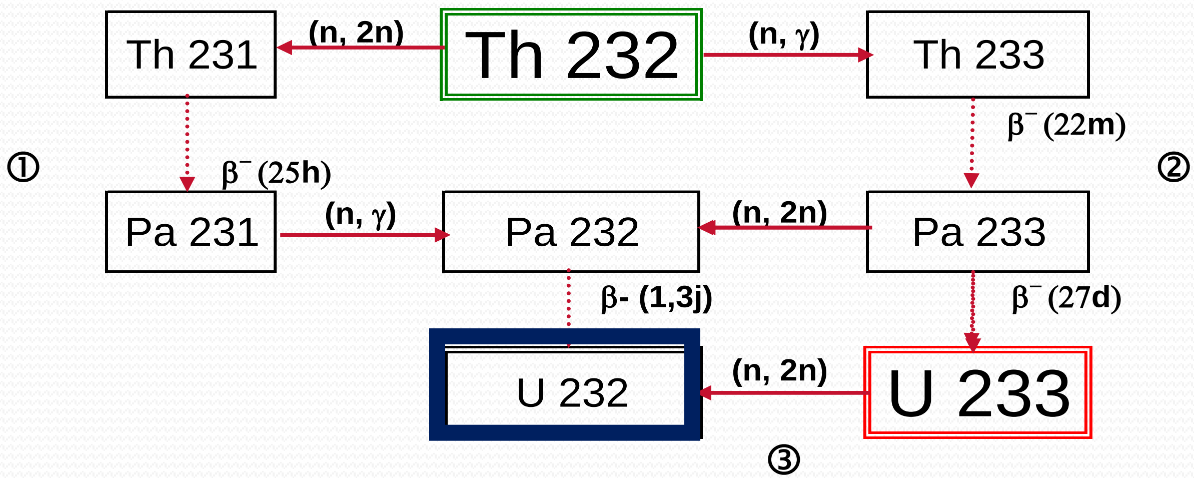
- Several processes have been developed in the past : powder pellet route (USA, India) Sol-gel processes (USA, Germany for HTRs), vibratory compaction (USA : ORNL and B & W), impregnation techniques, etc… (ref IAEA TECDOC – 1450)

- However, if Pu is used as fissile material, automation of the process and remote operation in shielded glove boxes are needed (experience do exist as well here : Lingen (BWR) and Obrigheim (PWR) in Germany).

- For U233 based fuel, hot cells are required (see « refabrication »)

The U232 Issue

U232 build up in a reactor using Th cycle



Radiation emission of U232 decay chain

U 232 $\xrightarrow{\textit{76 y } (\alpha)}$ ***(short lived intermediates : Th/Ra…)*** → ***Bi 212*** → ***Tl 208***

Very energetic γ emission of Bi 212 and especially Tl 208 2,6 Mev

Challenges for thorium cycle industrial development (3/3)

- Thorium cycle is much more attractive if U233 is recycled. Thus, reprocessing of thorium based fuel should be considered and investigated

- Reprocessing of thorium based fuels :
  - A process exists and has been tested at a small scale in the past : the **THOREX** process (operated at ORNL for many years)
  - However, this is somewhat **more challenging** than that of uranium based fuel because corrosive fluoride ion must be used for efficient dissolution
  - THOREX process is expected to generate 50-70 % more glass than PUREX (Indian study)
  - In any case significant R & D programs would be needed to develop a competitive industrial process

- Refabrication of U233 based fuels :
  - This is **a major technical hurdle** for the thorium cycle : refabrication of U233 bearing fuels MUST BE MADE in remote handling facilities (because of high radiation level of unavoidable U232 daughter products). This is feasible but would be costly and would need significant technological developments.

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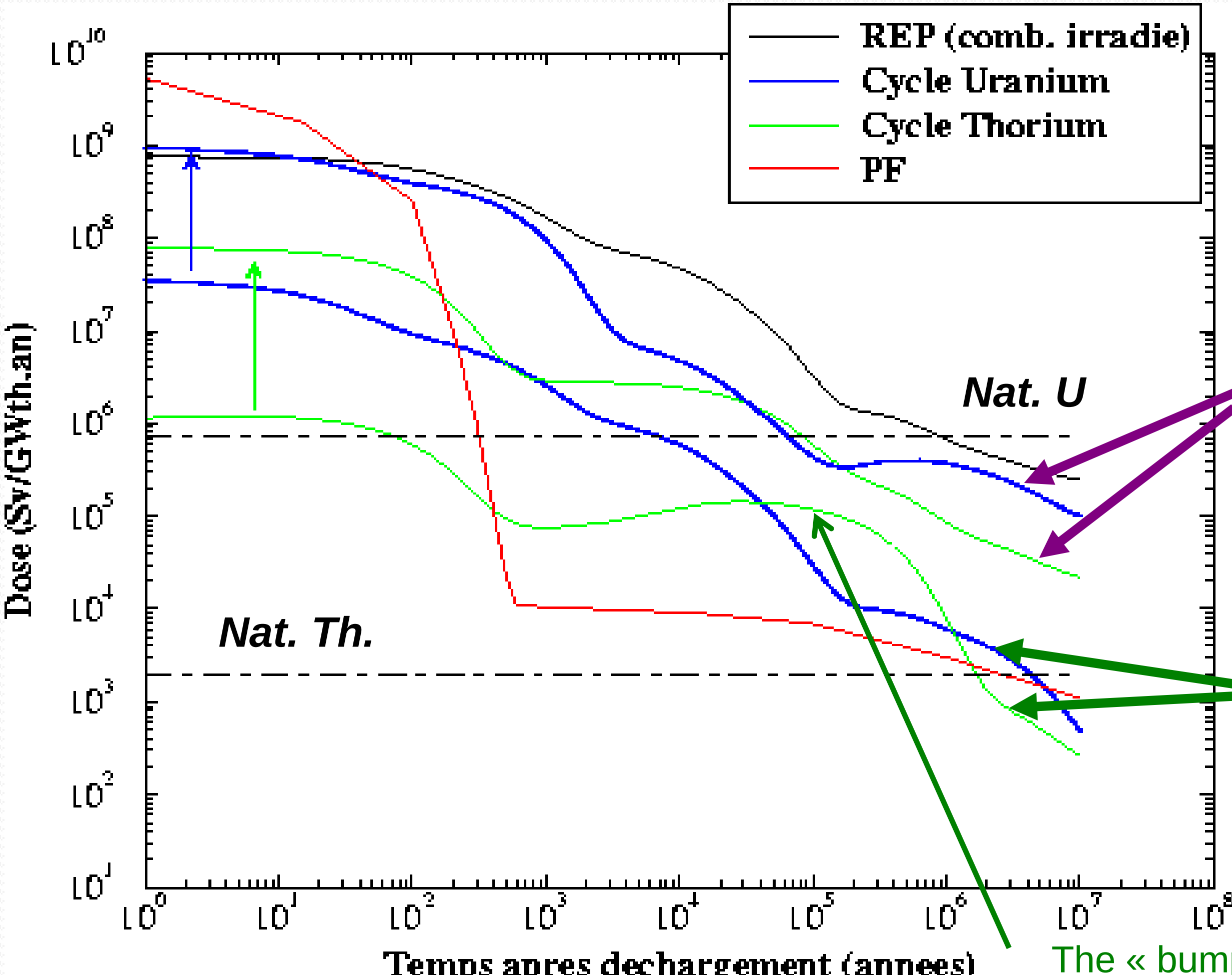
Comparison of radiotoxic inventories (from CNRS)

Uranium and thorium, cycles - With or without recycling of MAs



Without MA recycling
0.1% fertile/fissile
100% of MAs

With MA recycling
0.1% fertile/fissile
1% of MAs

The « bump » is due to Pa231 (produced by (n,2n) reactions on Th232), which half live is 33000 years

Proliferation issues

A « Gun type » nuclear weapon is feasible with U233

In April 15, 1955, US tested a nuclear weapon which core used a composite of uranium-233/ and plutonium test (this was part of the "Teapot" test series)

(Source : National Nuclear Security Administration/Nevada Site Office)

Conclusion on U233 nuclear weapon feasibility

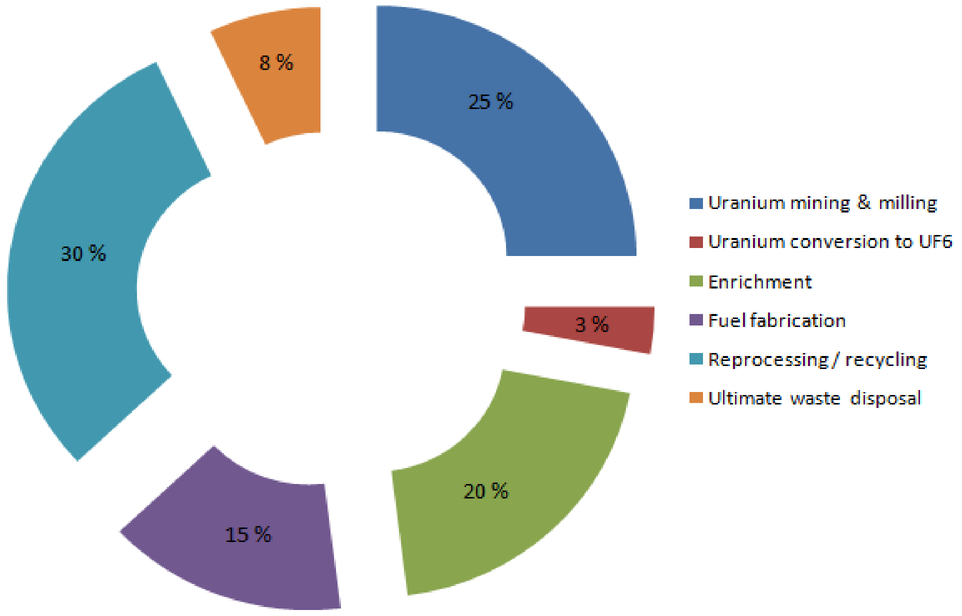
Nevertheless…

all "proliferation pathways" are not easy to implement and this should make thorium cycle a little bit more "proliferation resistant" than the standard U/Pu cycle

This was confirmed by specific studies on this topic, (using the SAPRA methodology: Bruno Pellaud, private report)

Economy

The relative parts of the costs of every stage of a standard uranium / plutonium « closed » fuel cycle (involving reprocessing of spent fuels and recycling of fissile nuclear materials, U & Pu) are the following[(1)]:



A detailed analysis shows that:

there should not be significant difference between U based and Th based cycles

(1) : Rounded figures – Updated figure from 1994 NEA study

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Feedback experience on thorium cycle

- Reactors:
  - Mainly HTRs but also some feedback PWR, BWR and MSR prototypes (see details before)

- Fuel Cycle:
  - Mines: about **25 000 tons already extracted** (monazites)
  - Separation / purification: more tricky than U (rare earths)
  - Fabrication: several « pre-industrial » process tested in the past
  - Reprocessing : THOREX (Oak Ridge), but tricky (Fluor ➔ corrosion)
  - Refabrication of U233 fuels almost no experience

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General Conclusion

Ultimately, it appears that thorium cycle presents real attractive features and could contribute to the sustainable development of nuclear energy.

In this perspective, it deserves to be further investigated.

R&D programs are thus needed to better assess its potential interests and to develop new processes and innovative technologies able to improve the conditions of its implementation

In this frame, the priority is to develop and qualify a FUEL which is the « corner stone » of any fuel cycle. To this regard, Th/Pu fuels seems a promising option for a thorium cycle

Thank you ....

COMPLEMENTARY SLIDES

The generation of U233

Th 232 + n → Th 233

β^- *(22 min.)*

Pa 233

β^- : *27 days*

U 233 ***(1.5 10^5 y)***

This is comparable to …

U 238 + n → U 239

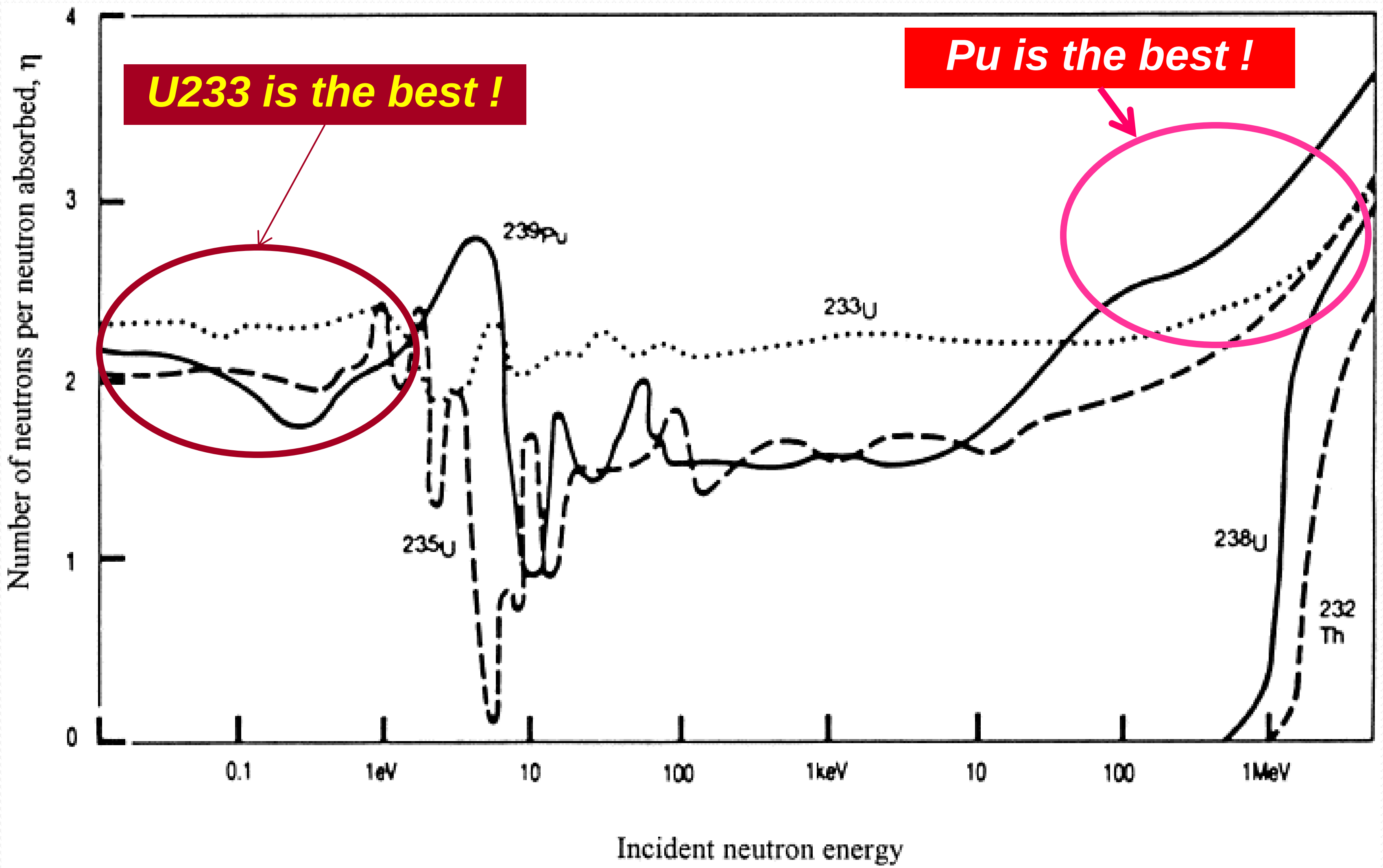
β^- *(23,5 min.)*

Np 239

β^- *(2,3 days)*

Pu 239 ***(24000 y)***

The "reproduction factor" η as function of energy of neutrons



World thorium reserves

There is considerable disagreement on what precisely are the world's economic resources of thorium.

Country	USGS (a)	IAEA 2009 (b)	IAEA 2012 (c)	Comments
CIS (1)		-	150 000	(1) : Arménia, l'Azerbaidjan, Belarus, Kazakstan, Kyrgystan, Moldavia, Tajikistan, Ousbekistan, Turkmenistan, Ukraine
Brazil	16 000	632 000	953 000	Very large gap between USGS and IAEA
India	290 000	319 000	846 500	Large increase in the IAEA 2012 estimation
Turkey	-	-	812 000	A new comer !
Australia	300 000	452 000	474 000	
USA	160 000	674 000	434 000	USGS post a very low figure compared to IAEA
Egypt	-	380 000	380 000	
Norway	170 000	264 000	320 000	
Venezuela	-	300 000	300 000	
Canada	100 000	172 000	172 000	
Russian fed.	-	75 000	155 000	
South Africa	35 000	148 000	148 000	USGS post a very low figure compared to IAEA
Greenland	-	86 000	89 500	
Malaysia	4 500	-	-	
OTHERS	124 500	114 000	1 879 500	
TOTAL	**1 200 000**	**3 616 000**	**7 113 500**	

(a) : US Geological Survey, Mineral Commodity Summaries, January 2005

(b) : IAEA-OECD "Red book", 2009: "Uranium resources, production and demand - "identified" (< 80 USD/Kg) + "inferred" resources

(c) : Prelimnary data presented in 2012 by Harikrishnan of IAEA - Currently under review by an Expert Group on thorium Resources, chaired by Dr Fritz Barthel. - 20 other countries are identifies in this study.

Comparison of Nuclear properties of the main fissile isotopes

		Thermal range (at 0,025 ev)			Fast range (SFR neutron spectrum)		
		U233	U235	Pu239	U233	U235	Pu239
σ (barn)	Fission (σ_f)	525	577	742	2,79	1,81	1,76
	Capture (σ_c)	46	101	271	0,33	0,52	0,46
Average number of neutrons per fission υ		2,498	2,442	2,880	2,53	2,43	2,94
η - 1 $\eta = \frac{\upsilon.\sigma_f}{\sigma_f + \sigma_c}$		**1,30**	1,08	1,11	1,27	0,88	**1,33**
Delayed neutron fraction (βeff) x 10^{-5}		267	650	210	About the same as in thermal range		

βeff for U233 is twice lesser than that of U235

Energy released per fission (Mev) : 190,7 for U233 compared to 193,7 for U235 and 202 for Pu239

Comparison of some physical and chemical properties of thorium and uranium

	U	Th	UO_2	ThO_2
Theoretical density	18,9	10,96	11,7	10
Thermal conductivity ($w.m^{-1}.K^{-1}$)	27,6	54	3 to 4 (1)	5 (1)
Melting point (°C)	1135	1750	2800	3300
Resonance integral (barns)	285	85	-	-
Thermal capture C.S. (barns)	2,7	7,4	-	-

(1) – Value given at 800 °C - This value decreases with temperature and it depends on the porosity of the matrix

<u>CONCLUSION :</u>

$Th0_2$ has better thermal properties than UO_2

Decay chain of Th 232

Isotope	Nom	Mode de désintégration	Période radioactive (= demi vie)	Énergie du rayonnement (MeV) – Cf. note	Produit de décroissance
$_{90}Th^{232}$	Thorium	α	$1{,}41 \times 10^{10}$ a	4,012	$_{88}Ra^{228}$
$_{88}Ra^{228}$	Radium	(β^-, γ)	5,74 a	0,0458	$_{89}Ac^{228}$
$_{89}Ac^{228}$	Actinium	(β^-, γ)	6,14 h	2,124	$_{90}Th^{228}$
$_{90}Th^{228}$	Thorium	α	1,91 a	5,42	$_{88}Ra^{224}$
$_{88}Ra^{224}$	Radium	α	3,63 j	5,68	$_{86}Rn^{220}$
$_{86}Rn^{220}$	Radon	α	55,8 s	6,29	$_{84}Po^{216}$
$_{84}Po^{216}$	Polonium	α	145 ms	6,906	$_{82}Pb^{212}$
$_{82}Pb^{212}$	Plomb	(β^-, γ)	10,6 h	0,5699	$_{83}Bi^{212}$
$_{83}Bi^{212}$	Bismuth	(β^-, γ) – 64 %	1 h	2,255	$_{84}Po^{212}$
		α – 35,9 %		6,207	$_{81}Ti^{208}$
		(β^-, α) – 0,014 %		11,206	$_{82}Pb^{208}$
$_{84}Po^{212}$	Polonium	α	299 ns	8,954	$_{82}Pb^{208}$
$_{81}Tl^{208}$	Thallium	(β^-, γ)	3,1 min	4,996	$_{82}Pb^{208}$
$_{82}Pb^{208}$	Plomb	–	STABLE	–	–

(1) Les valeurs trouvées dans la littérature ne sont pas toujours concordantes. Nous avons pris ici celles qui sont indiquées dans [14] pour la plupart des énergies de désintégration α, complétées au besoin par quelques autres valeurs trouvées dans divers recueils de données nucléaires.

U232 (72 years)

Thoron (Gas)

Nuclear reactors having used thorium

Nuclear reactors using (or having used) thorium fuels (partially or completely)						
Country	**Name**	**Type**	**Power (MW)**	**Startup date**	**Fuel**	**Comments**
USA	Indian point 1	PWR	265_e	1962	ThO2 - UO2	Pow er includes 104 Mw e from oil-fired superheater
	Elk River	BWR	22_e	1964	ThO2 - UO2	Pow er includes 5 Mw e from coal-fired superheater. Th loaded in the first core only
	Shippingport	PWR	60_e	1957	ThO2 - UO2	Used both U235 and Pu as the initial fissile material. Successfully demonstrated thermal breeding using the "seed/blanket" concept (TH/U233)
	Peach Bottom	HTR	40_e	1967	ThC2 - UC2	Coated particles fuel in prismatic graphite blocs - TH/HEU
	Fort St. Vrain	HTR	330_e	1976	ThC2 - UC2	Coated particles fuel in prismatic graphite blocs - TH/HEU
	MSRE	MSR	10_{th}	1965	ThF4 - UF4	Did operate w ith U233 fuel since october 1968 - No electricity production
UK	Dragon	HTR	20_{th}	1964	ThC2 - UC2	Coated particles fuel - No electricity production - Many types of fuel irradiated
Germ.	AVR	HTR	15_e	1967	ThC2 - UC2	Coated particles fuel in pebbles - Maximum burnup acheived : 150 GWd/t - TH/HEU
	THTR	HTR	300_e	1985	ThC2 - UC2	Coated particles fuel in pebbles - Maximum burnup acheived : 150 GWd/t - Th/HEU
	Lingen	BWR	60_e	1968	Th / Pu	Th/Pu w as only loaded in some fuel test elements
India	Kakrapar (KAPS) 1 - 2	PHWR	200_e	1993/95	UO2-ThO2	Fuel : 19-elements bundles. - 500 kg of Th loaded
	Kaiga 1 - 2	PHWR	200_e	2000/03	UO2-ThO3	Fuel : 19-elements bundles. Th is used only for pow er flattening
	Rajasthan (RAPS) 3 - 4	PHWR	200_e	2000	UO2-ThO4	Fuel : 19-elements bundles. Th is used only for pow er flattening
	KAMINI	Neut. S.	30 Kwe	-	U233	Experimental reactor used for neutron radiography
Th. fuels have been also tested in several experimental reactors : CIRUS (India), KUCA (Japan), MARIUS (France), etc.						

Advantages of HWR with regard to neutron « economy » and conversion ratio

- Much less reactivity change along fuel depletion because of « on line » refueling ➔ reduces the need for control poisons and thus “sterile” neutron captures in this poisons

- Much less neutron captures by Heavy water (compared to light water : capture C.S is 500 times less)

Example of neutron balance fo a « high conversion « HWR (Th-U-233)

***2,29 fast neutrons* produced following the absorption of 1 neutron by fissile material (U233)**

- ***0,91** captured by fertile material (Th232) leading to fissile production ➔ CR = 0,91*
- ***1** absorbed by fissile material*
- ***0,02** absorbed by heavy water*
- ***0,24** absorbed by fission products and structures*
- ***0,09** absorbed by other materials including control poisons*
- ***0,03** lost by leakage*

Total = 2,29

Challenges for thorium cycle industrial development

- **Mining**

  - Large efforts of thorium ore prospection would be needed (but in the long term, if thorium cycle is developed at a large scale)

  - External irradiation is much higher than in the uranium case before Th232 purification step (because of Tl-208)

  - However, mining of open pit monazite deposits (presently the main source of thorium) is easier than that of most uranium bearing ores

  - Management of thorium mine tailings is also simpler than in the case of uranium mainly because of the much shorter half live of « thoron » (= Rn 220 : 55 sec) than of radon (Rn 222 : 8 days, daughter of Ra 226, 1600 years)

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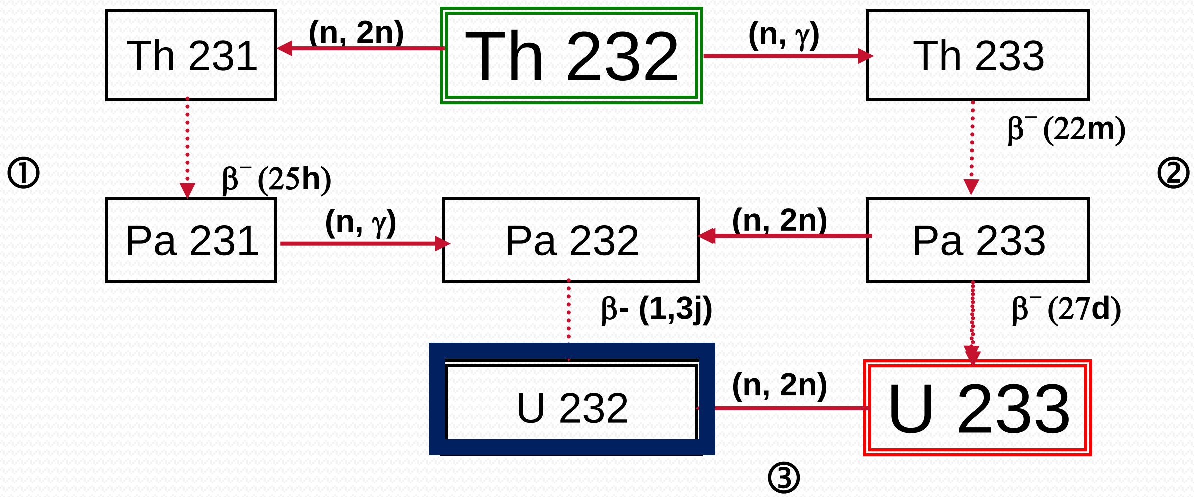
The U232 Issue

- U232 build up in a reactor using Th cycle



Radiation emission of U232 decay chain

U 232 $\xrightarrow{\text{76 y }(\alpha)}$ ***(short lived intermediates : Th/Ra…)*** → ***Bi 212*** → ***Tl 208***

Very energetic γ emission of Bi 212 and especially Tl 208 2,6 Mev

Challenges for thorium cycle industrial development

- Thorium cycle is much more attractive if U233 is recycled. Thus, reprocessing of thorium based fuel is should be investigated

- Reprocessing of thorium based fuels :
  - A process exists and has been tested at a small scale in the past : the **THOREX** process (operated at ORNL for many years)
  - However, this is somewhat **more challenging** than that of uranium based fuel because corrosive fluoride ion must be used for efficient dissolution
  - THOREX process is expected to generate 50-70 % more glass than PUREX (Indian study)
  - In any case significant R & D programs would be needed to develop a competitive industrial process

- Refabrication of U233 based fuels :
  - This is **a major technical hurdle** for the thorium cycle : refabrication of U233 bearing fuels MUST BE MADE in remote handling facilities (because of high radiation level of unavoidable U232 daughter products). This is feasible but would be costly and would need significant technological developments.

Mitigation of proliferation risk with U233

- The main obstacle comes from high radiations emission from U232 (daugter products)

- However it exists various means to cope with these difficulties (see next slide)

- Conversely, deterrent measures can be implemented such as mixing Th with U238 (but one produce Pu!) or dilution of U233 with U238 at reprocessing step. Nevertheless these measures should be investigate carefully in order to minimize potential negative effects on the interest of thorium cycle itself.

The U 232 issue for making a nuclear weapon (1/2)

Example of radiation level (at 1 meter) for a 10 kg sphere of U233 containing 0.5 % to 1 % U232 :

Time after Separation of U233 + U232	Rem/h (100 Rem = 1 Sv)	Note
1 month	**11 (110 mSv) / h**	• **ICRP limit for workers: 5 rem/Y**
1 year	**110 (1,1 Sv) / h**	• **Clinical effect for a dose > 100 rem**
2 years	**200 (2 Sv) / h**	• **Lethal dose: 800 rem (8 Sv)**

Note **:** *Radiation can be a safety problem for a fully assembled weapon with U233 but it can be largely reduced by thick tampers in a crude device*

The U 232 issue for making a nuclear weapon (2/2)

Means to manage the problem include :

- Weapon fabrication soon after U233 separation (for example 2 – 3 weeks)
- Remote weapon fabrication : feasible but require rather sophisticate technology
- **Reduce U232 buildup** in the reactor : either in **thermal reactors** by **limiting** strongly the **burn up** of thorium bearing fuels, or recover U233 **in FNRs thorium blanket** (this can reduce U232 content by a factor ten (< 0.05 %) or even much more)[(1)]
- **Isolate Pa233 ! (MSR ?)**
- U232 Laser isotopic separation (India)

(1) : US did produce in the 50s 130 kg U233 with about 50 ppm of U232 and even 400 kg with only 7 ppm of U232. - See BOSWELL (J.M.) et col. – Production of 233U with Low 232U Content in the proceedings of the Gatlingburg, symposium (slide 4)

Take away points (1/3)

- Thorium resources are at least as abundant as uranium
- Front-end thorium fuel cycle operations do not raise significant difficulties compared to uranium cycle (and there is already some industrial experience on this activities)
- Recycling operation are much more challenging because thorium based fuel are difficult to dissolve and because fuel fabrication with U233 must be made in remote handling facilities
- Radiotoxic inventory of ultimate **waste** from thorium cycles decreases much sooner than the one of U/Pu cycles: **it is a real potential asset**

Take away points (2/3)

- Thorium cycles have been widely investigated in the past. These studies show that virtually every type of reactors can accommodate thorium based fuels

- The use of thorium in reactors presents some drawbacks (high concentration of Pa233 for example) but also several advantages (possibility of high burnup, very high melting point of ThO2,…)

- From non proliferation point of view, thorium cycle appears to have some interesting features, thanks to the « U232 barrier »

Take away points (3/3)

- Thorium <u>IS NOT</u> a <u>SUBSTITUTE</u> to <u>URANIUM</u> and it must be mixed with a fissile material:
  - To this regard, Th-Pu fuel cycle seems to be the most attractive option
  - However, for conventional thermal reactors **<u>with low conversion ratios</u>**, its use does not significantly reduce uranium needs compared to the U/Pu cycle
  - For advanced « <u>near breeder</u> » or breeder thermal reactors (which industrial development would need large R&D efforts) uranium savings can become very significant. **<u>This another real potential asset.</u>**