THE UTILIZATION OF THORIUM IN ADVANCED PWR- FROM SMALL TO BIG REACTORS

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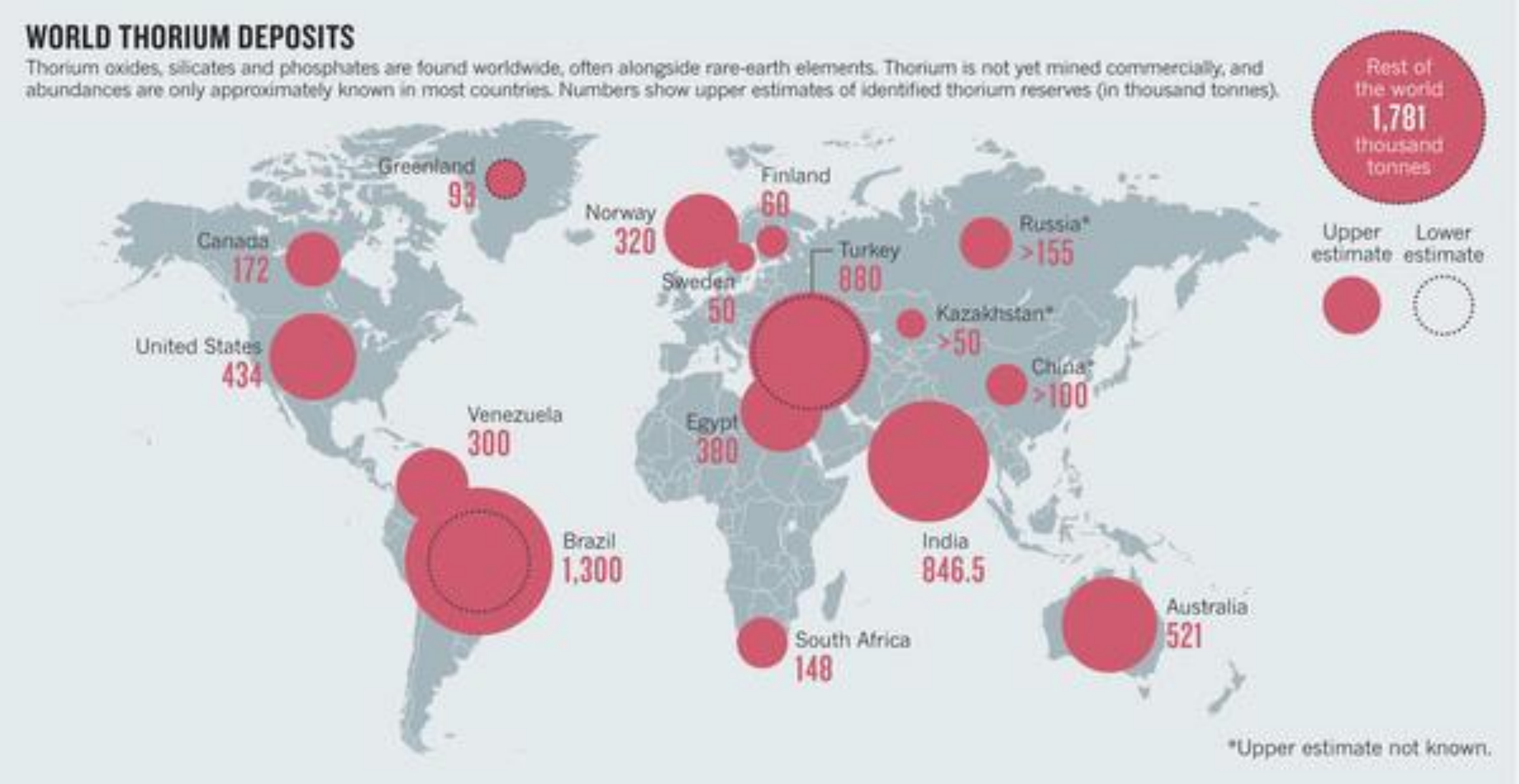
THORIUM

Thorium (Th) is an actinide, metallic element, and it is named for “ Thor”, the Scandinavian god of war by his discover, Jöns Borzelius, a Sweden in 1829. The abundance of Th in the earth is 6,000 ppb, three times that of uranium, and it is found naturally in its isotope ^{232}Th (100%), being radioactive (T1/2= 1.4x10^{10} years), and in its natural chain decay produces isotopes like

^{228}Ra; ^{228}Ac; ^{228}Th, ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{208}Tl to a stable ^{208}Pb

Thorium Reserves



WORLD THORIUM DEPOSITS

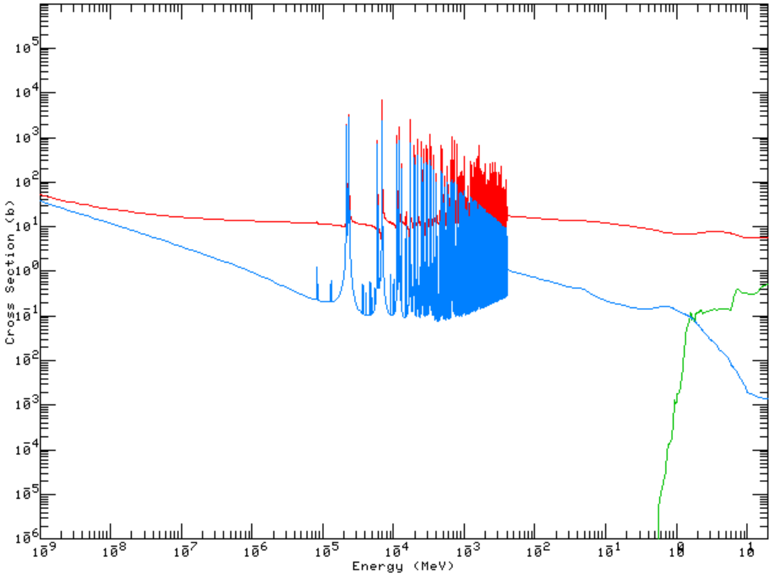
Thorium oxides, silicates and phosphates are found worldwide, often alongside rare-earth elements. Thorium is not yet mined commercially, and abundances are only approximately known in most countries. Numbers show upper estimates of identified thorium reserves (in thousand tonnes).

*Upper estimate not known.

Most of naturally thorium resources is found in the form of ThO_2 (Thorianite), $ThSiO_4$ (Thorite) or in monazite sand (mixture of Calcium, Cerium, Thorium, and other rare-earth elements).

Nuclear Characteristics of Thorium

$^{232}\mathrm{Th}(n,\gamma)^{233}\mathrm{Th} \rightarrow {}^{233}\mathrm{Pa} \rightarrow {}^{233}\mathrm{U}$(fissile)

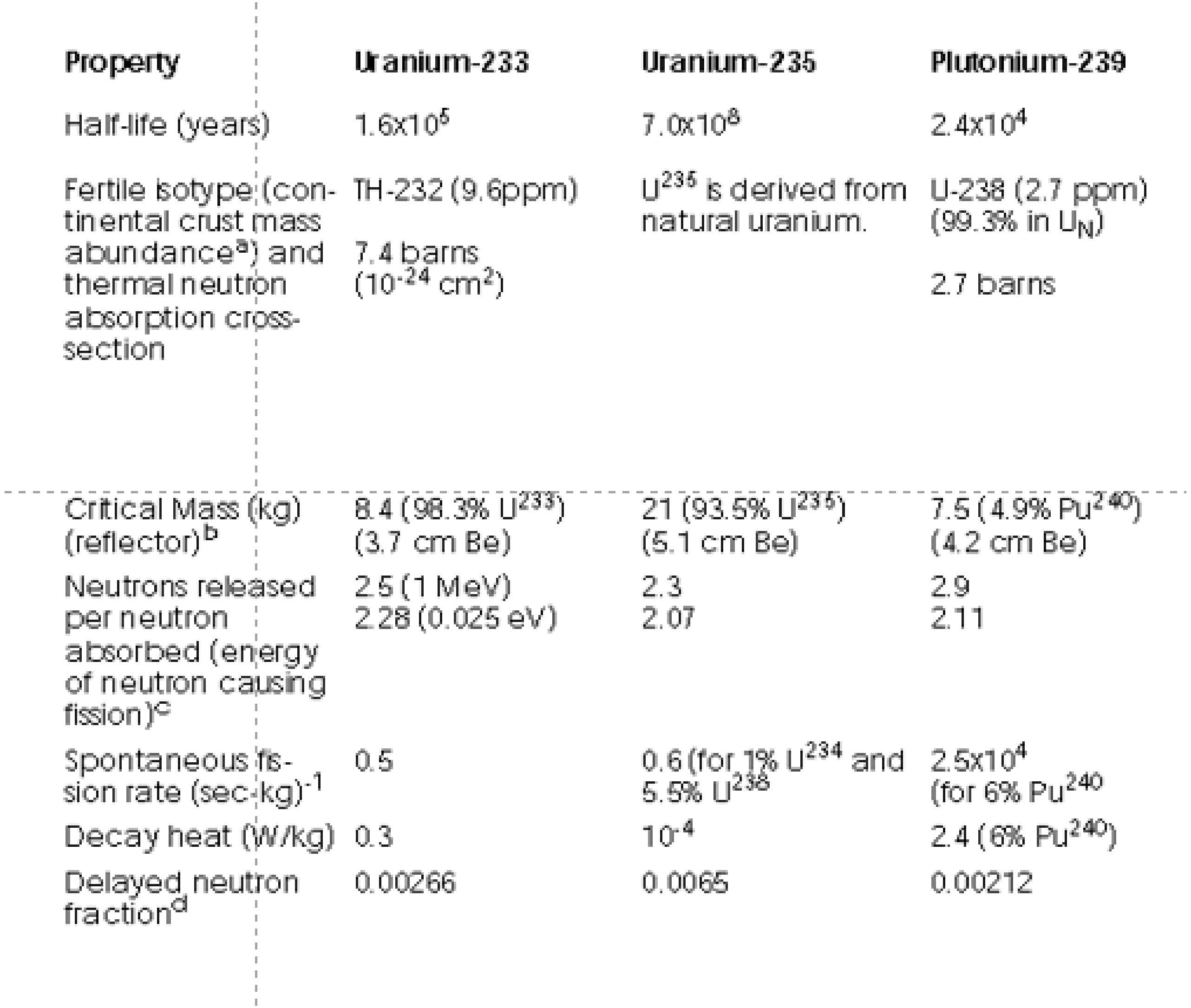


U-233 has the highest number of neutrons produced per neutron absorbed among all thermally fissile isotopes; neutron poison (Xenon and Samarium) production is 20% lower than other fissionable isotopes;

Mixed Oxide-Thorium Fuel
$(U_xTh_y)O_2$
$(Pu_xTh_y)O_2$

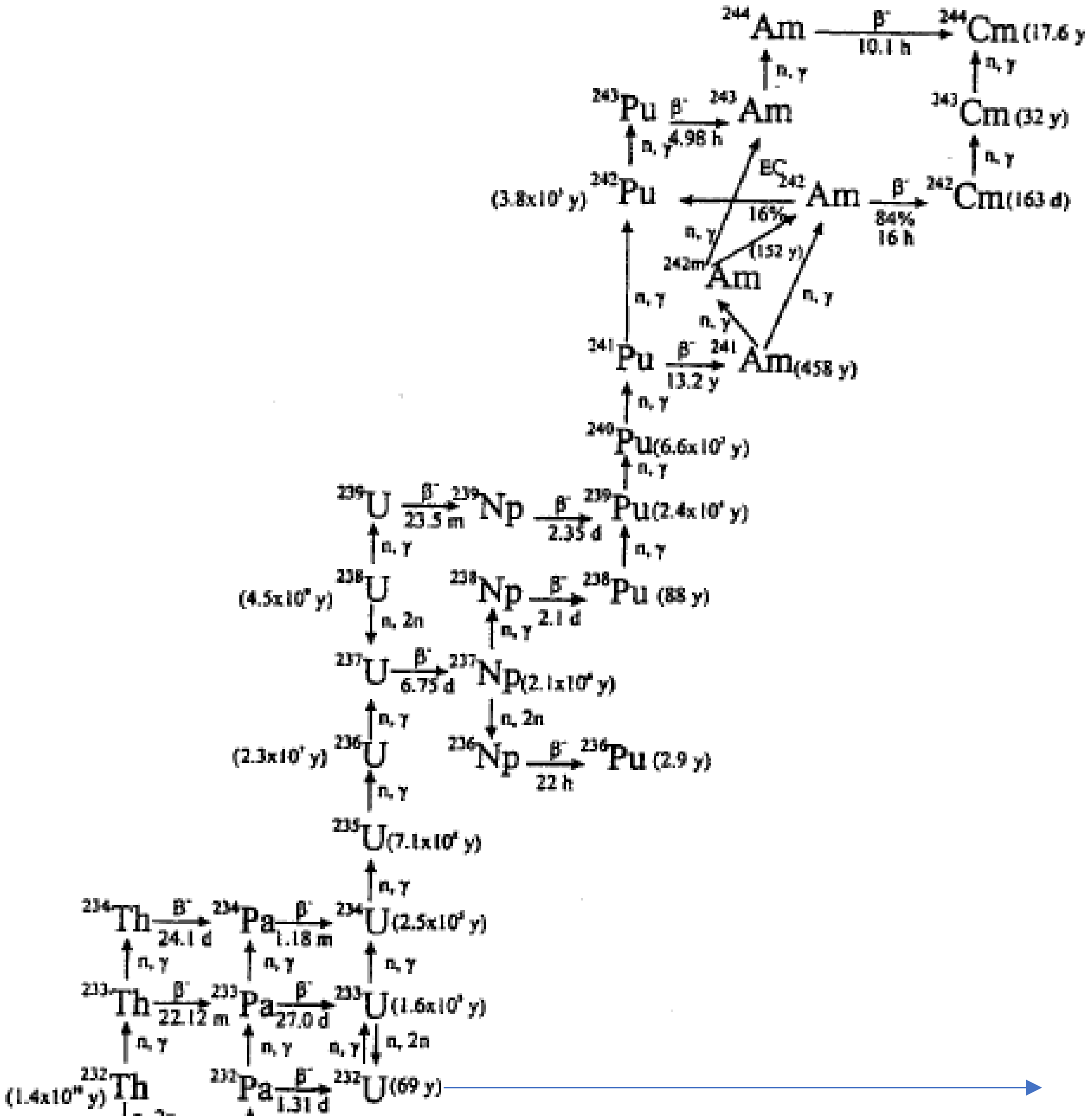
^{232}Th cross sections from ENDF-B-VI.
The red line is the total cross section, the blue line the absorption and the green line the fission

Nuclear Characteristics of Fissile Isotopes



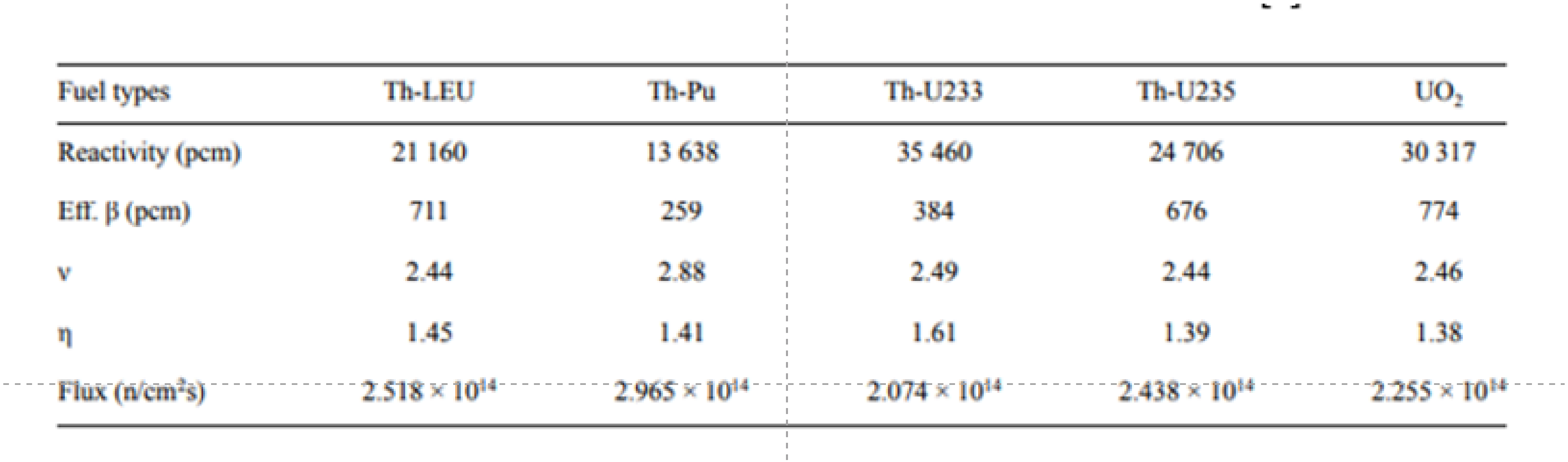
Property	Uranium-233	Uranium-235	Plutonium-239
Half-life (years)	1.6×10^5	7.0×10^8	2.4×10^4
Fertile isotope (continental crust mass abundance[a]) and thermal neutron absorption cross-section	TH-232 (9.6ppm) 7.4 barns (10^{-24} cm^2)	U^{235} is derived from natural uranium.	U-238 (2.7 ppm) (99.3% in U_N) 2.7 barns
Critical Mass (kg) (reflector)[b]	8.4 (98.3% U^{233}) (3.7 cm Be)	21 (93.5% U^{235}) (5.1 cm Be)	7.5 (4.9% Pu^{240}) (4.2 cm Be)
Neutrons released per neutron absorbed (energy of neutron causing fission)[c]	2.5 (1 MeV) 2.28 (0.025 eV)	2.3 2.07	2.9 2.11
Spontaneous fission rate $(sec \cdot kg)^{-1}$	0.5	0.6 (for 1% U^{234} and 5.5% U^{238}	2.5×10^4 (for 6% Pu^{240}
Decay heat (W/kg)	0.3	10^{-4}	2.4 (6% Pu^{240})
Delayed neutron fraction[d]	0.00266	0.0065	0.00212

Products of multiple-neutron captures on Th-232



Once irradiated in a reactor, the fuel of a thorium–uranium cycle contains an admixture of ^{232}U (half-life 68.9 years), which appear by the reaction ^{233}U(n,2n)^{232}U(n,γ)^{233}U, whose radioactive decay chain includes emitters (particularly ^{208}Tl) of high energy gamma radiation (2.6 MeV). This makes spent thorium fuel treatment more difficult, requires remote handling/control during reprocessing, or shielding thickness and during further fuel fabrication, but on the other hand, may be considered as an additional non-proliferation barrier

Neutronic characteristic of PWR cores with different mixed oxide fuels



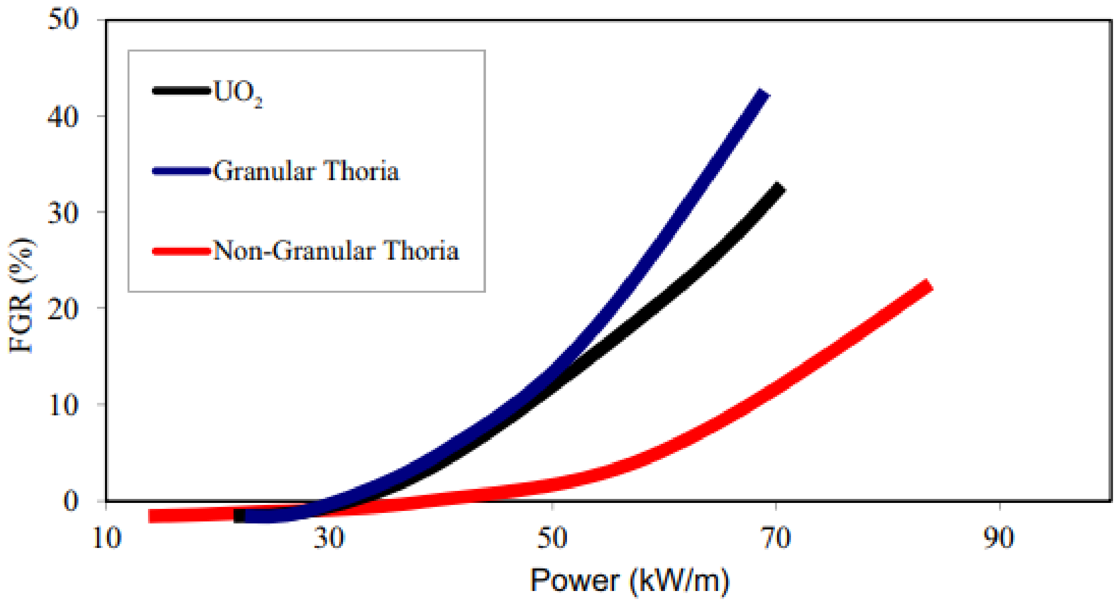
Fuel types	Th-LEU	Th-Pu	Th-U233	Th-U235	UO_2
Reactivity (pcm)	21 160	13 638	35 460	24 706	30 317
Eff. β (pcm)	711	259	384	676	774
ν	2.44	2.88	2.49	2.44	2.46
η	1.45	1.41	1.61	1.39	1.38
Flux (n/cm^2s)	2.518×10^{14}	2.965×10^{14}	2.074×10^{14}	2.438×10^{14}	2.255×10^{14}

Thermal Physics and Irradiation Properties of Th based fuels

- Thorium oxide (ThO_2) is relatively inert and does not oxidize further, unlike UO_2.
- ThO_2 has higher thermal conductivity compared with UO_2
- ThO_2 lower thermal expansion coefficients compared to UO_2
- ThO_2 has a much higher melting point (3300 °C) compared to UO_2
- $(Th\text{-}U)O_2$ has been qualified under irradiation in the 70’ and 80’ and has well know thermal physics properties
- Finally, a sophisticated data collection programme had been designed in which several thorium-plutonium oxide fuel pins were irradiated in simulated LWR conditions in the fuel-testing reactor in Halden, Norway. Accordingly, with a recent note published at Nuclear News [March, 2018], the experiments were successfully conducted

Fission Gas Released
FGR versus power density

- Fission gas release (FGR) is primarily dependent on power density (fuel temperature), with fuel burnup as a secondary variable. Figure plots FGR versus linear power density and compares UO_2 to granular and non-granular thorium. Below ~40 kW/m fuel microstructure plays a minimal role in FGR due to the low fuel temperature. The lines drawn in the figure represent data trends and demonstrate comparable performance between UO_2 and granular thorium; non-granular thorium demonstrates superior performance



THORIUM UTLIZATION IN PWR REACTORS

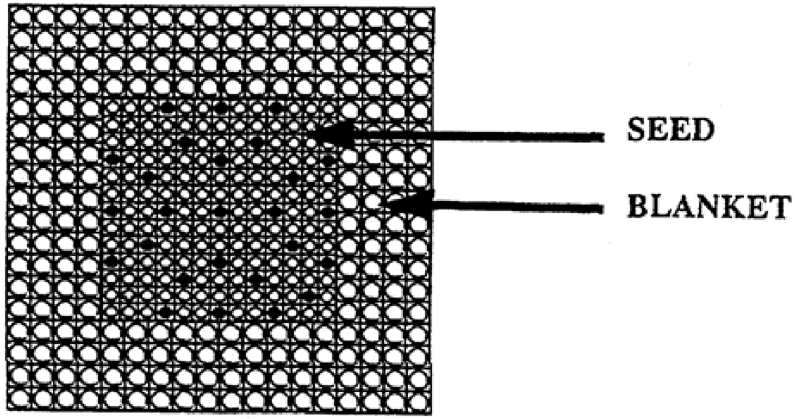
Several Th/U fuel cycles, using thermal and fast reactors were proposed and are still under investigation, such as the Radkowsky OTC for PWR, and the thorium fuel cycles for CANDU reactors. Thorium has been proposed as fuel for the molten salt reactor, the advanced heavy water reactor, High Temperature Reactors, Pebble Bed reactor, fast breeder reactors, and more recently for generation IV and ADS systems. Here the focus is going to be in PWR reactors, since it is the reactor presently more used in the world, and it is a strong candidate to uses thorium commercially.

Utilization of Thorium in PWR

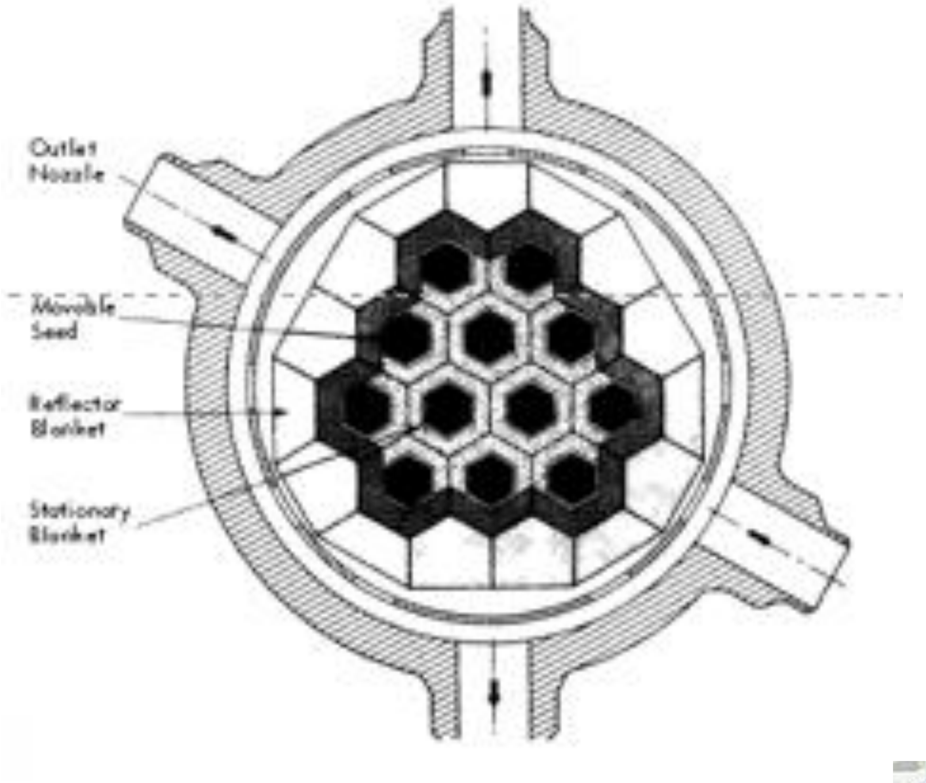
- PWR Indian Point Reactor number 1 (270 MWe), which was the first to utilize a core loaded with $(U\text{-}Th)O_2$, with high enriched U (93 wt%), and achieving a maximum burn up of 32 MWD/kg HM.
- The last core of the Shippingport PWR was loaded with ThO_2 and $(U\text{-}Th)O_2$ fuel rods using the seed-blanket concept and operated as a light water breeder reactor during 1200 effective full power days and reached a final burnup of 60 MWD/kg HM.
- The Radkowsky concept proposes a concept to be used in typical fuel elements of PWRs in which the seed is a U/Zr alloy, and the blanket an $(Th_{0.9}\text{-}U_{0.1})O_2$ oxide using low enriched uranium(RTF)
- In Brazil, in the framework of the Brazilian German agreement that a comprehensive research program about Th utilization in PWRs was conducted by the CDTN/NUCLEBRAS in Brazil and the former KFA in Germany aiming at analysing and proving the option of thorium utilization in PWRs . The program was conducted between 1979 and 1988, and defined core configurations of Th fuel cycles for standard 1300 MW Siemens PWRs; defined technical specifications for fuel technology of $(U\text{-}Th)O_2$ and $(Th\text{-}Pu)O_2$; studied fuel design and modelling, including the fuel behaviour in irradiation experiments at the FRJ-2 at KFA; studied the spent fuel treatment, including laboratory investigation on reprocessing spent thorium fuels with non-irradiated elements

RTF Fuel Element and Reactor
Shipping Port LWBR with Thorium

Parameter	Th-U Cycle	Th-Pu Cycle
Total Power(MW_{th})	3,400	3,400
Assemblies(SBU)	193	193
Seed/Blanket Vol. Fraction	0.4/0.6	0.5/0.5
Seed V_m/V_f	3.0	3.0
Blanket V_m/V_f	1.8	1.8
Seed Fuel	$U_{0.2}$/Zr alloy, 20 wt% ^{235}U	$Pu_{0.2}$/Zr alloy
Blanket Fuel	$(Th_{0.9}-U_{0.1})\ O_{2,}$, 20wt% ^{235}U	$(Th_{0.9}-Pu_{0.1})O_2$
In core fuel management	3 batch seed schemes, 300 Full Power Days	same

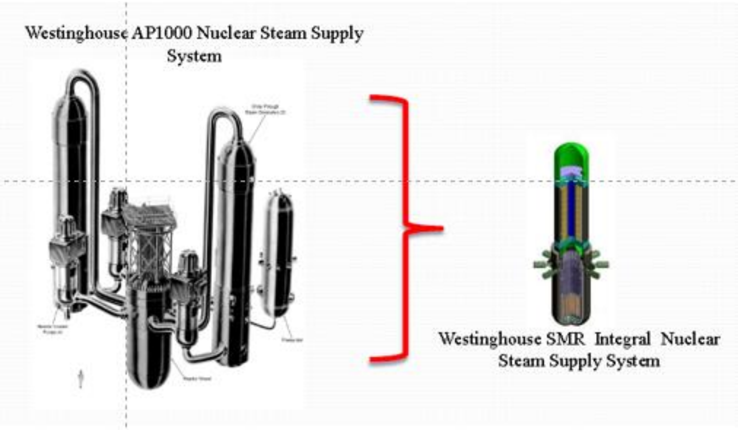


Shipping Port LWBR with Thorium



Recent studies in Thorium utilization in PWR

- Herring et al.[*Nuclear Engineering and Design,* 203, 65–85, 2001] studied the utilization of mixed thorium/uranium dioxide $(U\text{-}Th)O_2$ in a typical generation II PWR using a 17x17 type fuel assembly. The results showed that the $(U\text{-}Th)O_2$ cores could be burned to about 87MWD/ kg HM using 35 wt% UO_2 and 65 wt% ThO_2 with an initial enrichment of about 7 wt.% of the total heavy metal fissile material.
- Ashley et al.[*Annals of Nuclear Energy* 69, 314–330, 2014] discussed open cycles for thorium-fueled nuclear power systems, including the conversion of EPR.
- Baldova et al.[*Annals of Nuclear Energy*, 87. 517-526, 2016]discussed the use of high conversion Th-^{233}U fuels in current generation PWRs
- Lindley et al. [*Progress in Nuclear Energy*, 77, 107-123, 2014] studied thorium-fueled PWRs with reduced moderation and possible closed fuel cycles
- Tucker [*Annals of. Nuclear Energy*, 111, 163–175, 2018] have studied the using of a thorium–plutonium mixed oxide fuel for a Westinghouse-type 17x17 PWR



Advanced PWR: Small and Big

Given the loss of competitivity of the nuclear industry, the public opinion against nuclear generation, and safety issues, since the beginning of the century the industry launch new innovative designs to be competitive and safety improvement. These reactors, called in the West Word by Generation III, are already in advanced stage of projects, many of them in construction and operation. They are big reactors, with powers in the range of 1000 MWe, and more recently, small reactors with power less of 300 MWe. These reactors are still using the same type of fuel, i.e. UO_2, and the main characteristics remain almost the same as the Generation II Reactor but with improvements related to safety, economy and operational performance

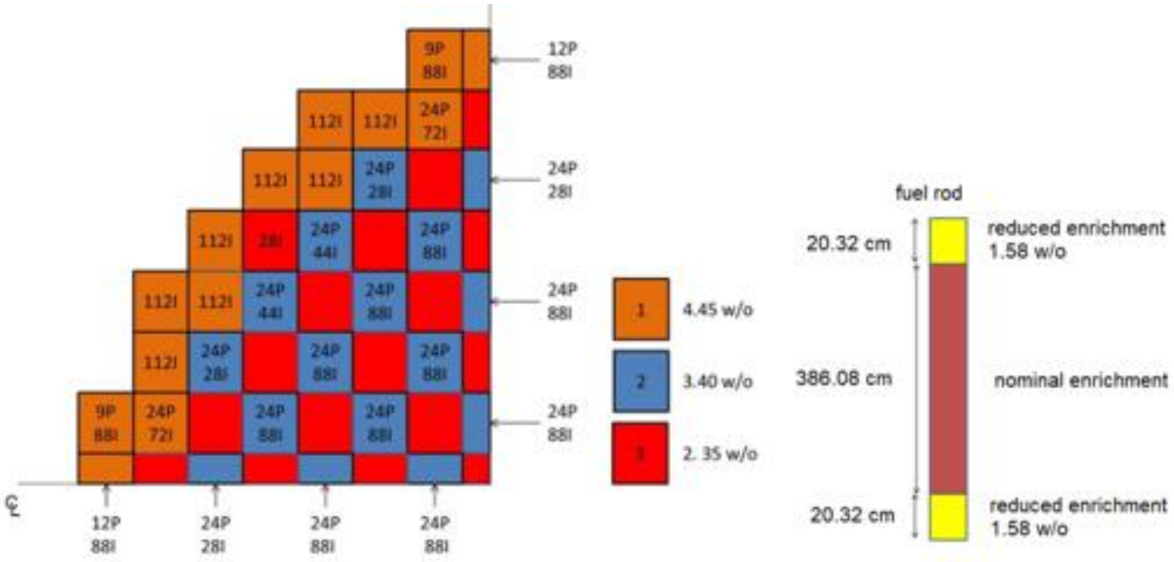
Advanced Big PWR Reactors(G-III)

Developer	Reactor	Size-MWe	Notes-Stage of Development
Advanced power reactors operational			
KHNP(Korea)	APR1400	1450	Shin Kori 4 in South Korea, operating since Jan 2016. Under construction: Shin Hanul 1&2 in South Korea, Barakah in UAE. Korean design certification 2003. US design certification application.
Gidropress(Russia)	VVER-1200	1200	Novovoronezh II, from mid-2016, as AES-2006. Under construction at Leningrad. Planned for Akkuyu in Turkey and elsewhere
Advanced power reactors under construction			
Westinghouse(USA)	AP 1000	1170	Under construction in China and USA, many units planned in China (as CAP1000). US design certification 2005, UK generic design approval 2017. Canadian design certification in progress.
Areva(France)	EPR	1630	Was to be future French standard, French design approval. Being built in Finland, France & China.
CNNC & CGN (China)	Hualong One	1170	Main Chinese export design, under construction at Fangchenggang and Fuqing, also Pakistan.
Advanced power reactors ready for deployment			
Mitsubishi(Japan)	APWR	1400	Planned for Tsuruga in Japan. US design certification application for US-APWR,but delayed. EU design approval for EU-APWR Oct 2014.
Areva & Mitsubishi	Atmea1	1150	Planned for Sinop in Turkey. French design approval Feb 2012. Canadian design certification in progress.
Gidropress	VVER-TOI	1300	Planned for Kursk II, Nizhny Novgorod and many more in Russia.

- Design Standardization to expedite licensing (pre-licensing), diminishing construction time implying in reducing the capital cost (economics criteria);
- Simplified Design to simplify the operation and reduce the operational faults;
- Greater availability, increase the time between refuelling, and increase the plant life time (60 year);
- Minimization of the possibility of Core Meltdown;
- Emergency coolant system, passive;
- Greater Burn up (60 MWD/ Kg U) and reduces the waste production;
- Utilization of advanced fixed burn up poison to increase the fuel lifetime.

AP 1000- Big Advanced PWR

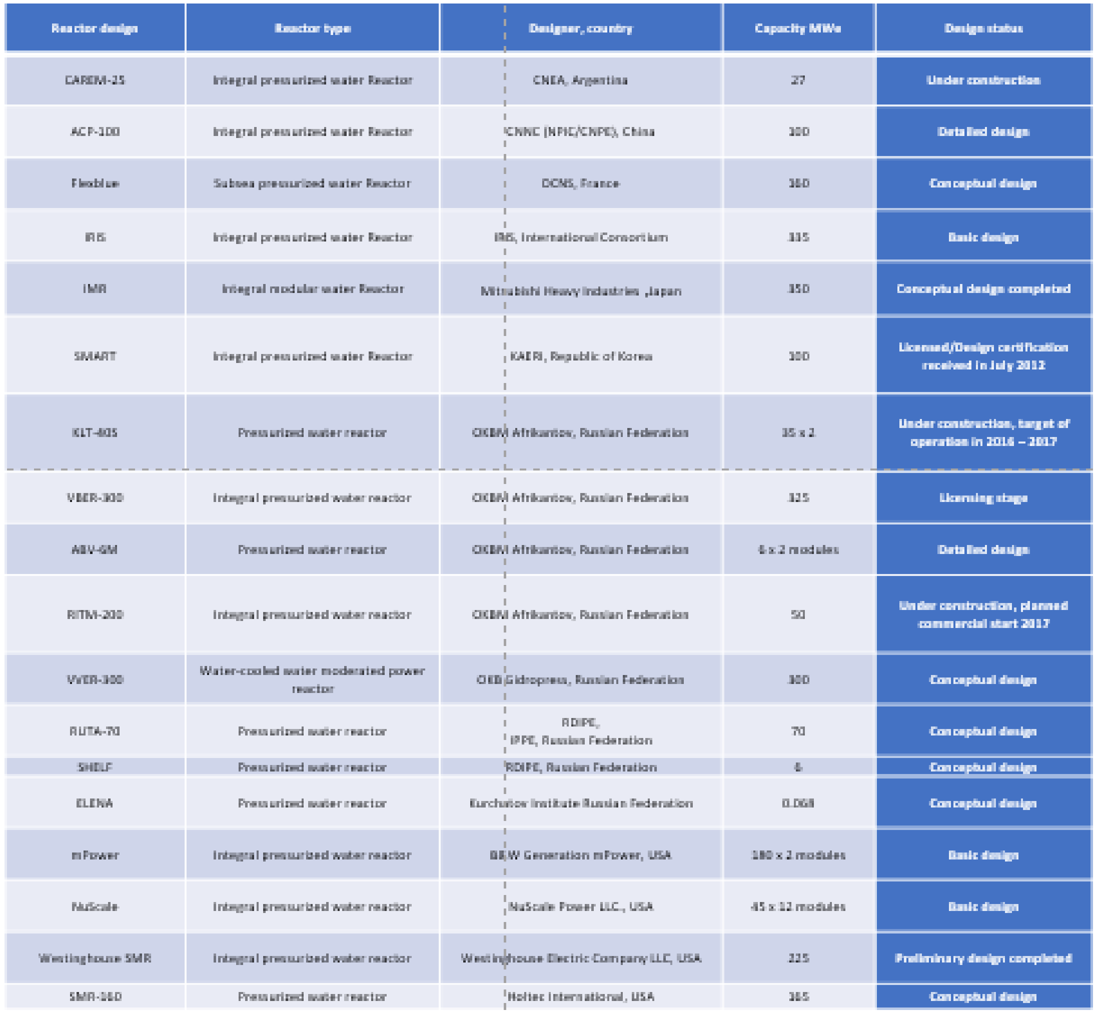
- The AP1000 advanced PWR reactor operates at a nominal power of 3400 MW thermal and contains 157 fuel assemblies with three different enrichment regions
- The beginning of cycle (BOC) core has two types of burnable poisons: The Integral Fuel Burnable Absorber (IFBA) and the Pyrex Burnable Absorber. The IFBA rods occupy some of the positions of the fuel rods while the Pyrex rods occupy some of the guide tube positions.
- Besides different radial enrichment zones, the fuel pins have also different axial enrichment
- Besides fixed burn up poison, the AP 1000, is controlled by control banks and soluble boron.



Advanced Small Modular Reactors- PWR

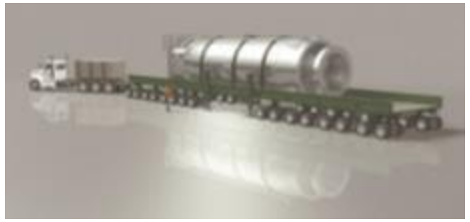
- There are many interests all over the world to use these kinds of reactors. There are diverse types of SMRs under distinct stages of design, licensing and in construction. Russia (KLT40s), Argentina (CAREM) and China (HTR-PM) have three types of SMRs under construction now and are scheduled to begin commercial operation between 2018 and 2020. Korean System Integrated Modular Advanced Reactor (SMART) has a certified design and Russian VBER-300 is under the licensing stage. There are many other SMR designs that will be prepared for near term deployment, although realistically it seems that the first commercial group of SMRs, start the operation near 2025 – 2030

Pressurized Water SMRs under developing all over the world

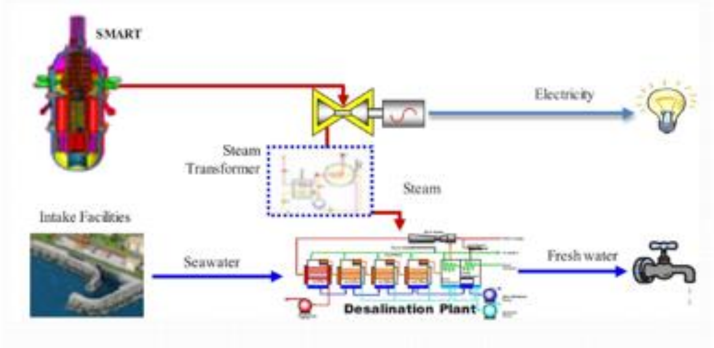


Reactor design	Reactor type	Designer, country	Capacity MWe	Design status
CAREM-25	Integral pressurized water Reactor	CNEA, Argentina	27	Under construction
ACP-100	Integral pressurized water Reactor	CNNC (NPIC/CNPE), China	100	Detailed design
Flexblue	Subsea pressurized water Reactor	DCNS, France	160	Conceptual design
IRIS	Integral pressurized water Reactor	IRIS, International Consortium	335	Basic design
IMR	Integral modular water Reactor	Mitsubishi Heavy Industries ,Japan	350	Conceptual design completed
SMART	Integral pressurized water Reactor	KAERI, Republic of Korea	100	Licensed/Design certification received in July 2012
KLT-40S	Pressurized water reactor	OKBM Afrikantov, Russian Federation	35 x 2	Under construction, target of operation in 2016 – 2017
VBER-300	Integral pressurized water reactor	OKBM Afrikantov, Russian Federation	325	Licensing stage
ABV-6M	Pressurized water reactor	OKBM Afrikantov, Russian Federation	6 x 2 modules	Detailed design
RITM-200	Integral pressurized water reactor	OKBM Afrikantov, Russian Federation	50	Under construction, planned commercial start 2017
VVER-300	Water-cooled water moderated power reactor	OKB Gidropress, Russian Federation	300	Conceptual design
RUTA-70	Pressurized water reactor	RDIPE, IPPE, Russian Federation	70	Conceptual design
SHELF	Pressurized water reactor	RDIPE, Russian Federation	6	Conceptual design
ELENA	Pressurized water reactor	Kurchatov Institute Russian Federation	0.068	Conceptual design
mPower	Integral pressurized water reactor	B&W Generation mPower, USA	180 x 2 modules	Basic design
NuScale	Integral pressurized water reactor	NuScale Power LLC., USA	45 x 12 modules	Basic design
Westinghouse SMR	Integral pressurized water reactor	Westinghouse Electric Company LLC, USA	225	Preliminary design completed
SMR-160	Pressurized water reactor	Holtec International, USA	165	Conceptual design

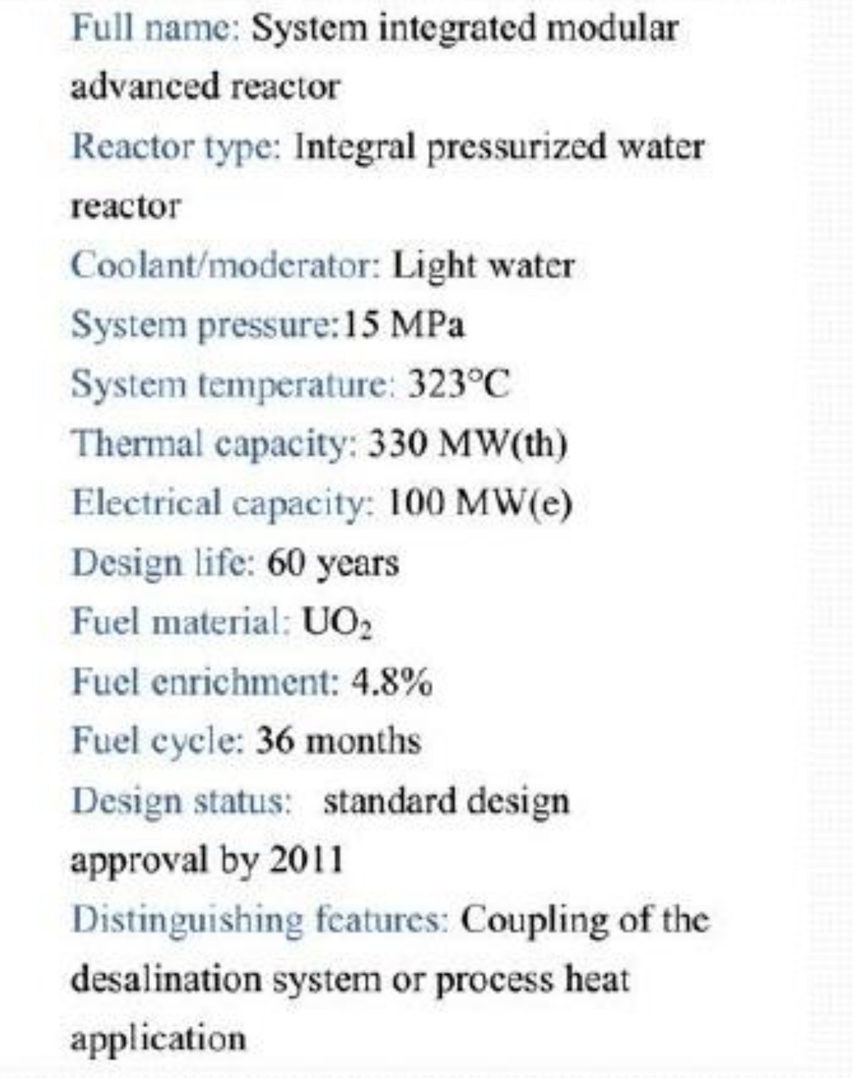
Advantages of SMRs over traditional nuclear power plants



- Flexible and Versatile
  - –Deployed faster and easier
  - –More easily integrated to electricity grids
  - –More flexible siting requirements (smaller footprint)
  - –Multiple units deployed side by side
  - –Offsite manufacturing vs onsite manufacturing (Portability)
- Suitable for multiple applications (e.g Electricity and Desalinization)
- Enhanced safety features
- Lower capital costs



SMART- Korean SMR



Full name: System integrated modular advanced reactor

Reactor type: Integral pressurized water reactor

Coolant/moderator: Light water

System pressure:15 MPa

System temperature: 323°C

Thermal capacity: 330 MW(th)

Electrical capacity: 100 MW(e)

Design life: 60 years

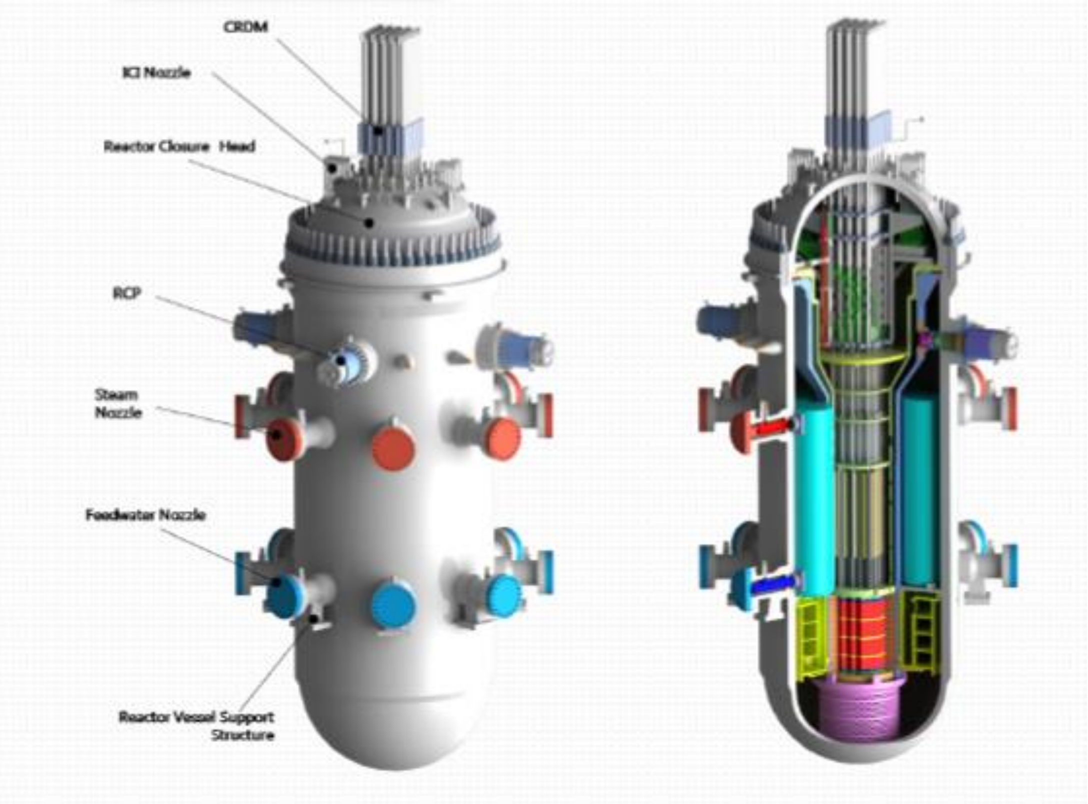
Fuel material: UO_2

Fuel enrichment: 4.8%

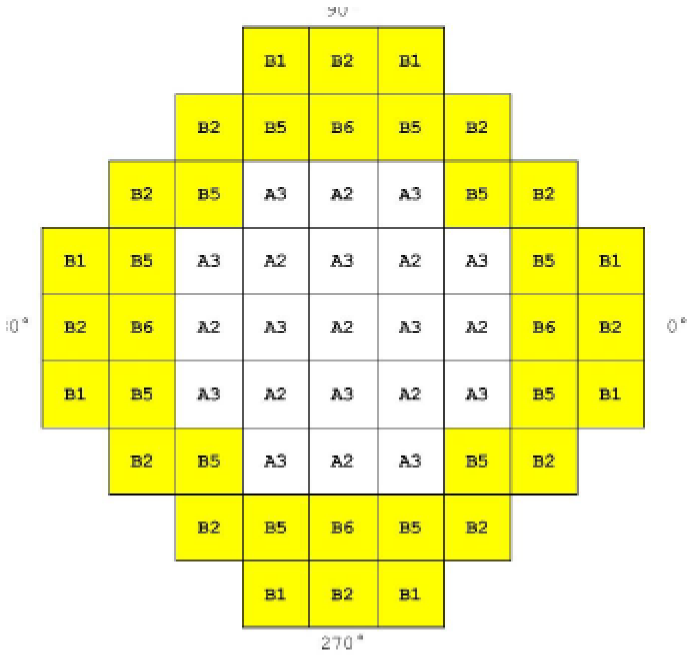
Fuel cycle: 36 months

Design status: standard design approval by 2011

Distinguishing features: Coupling of the desalination system or process heat application

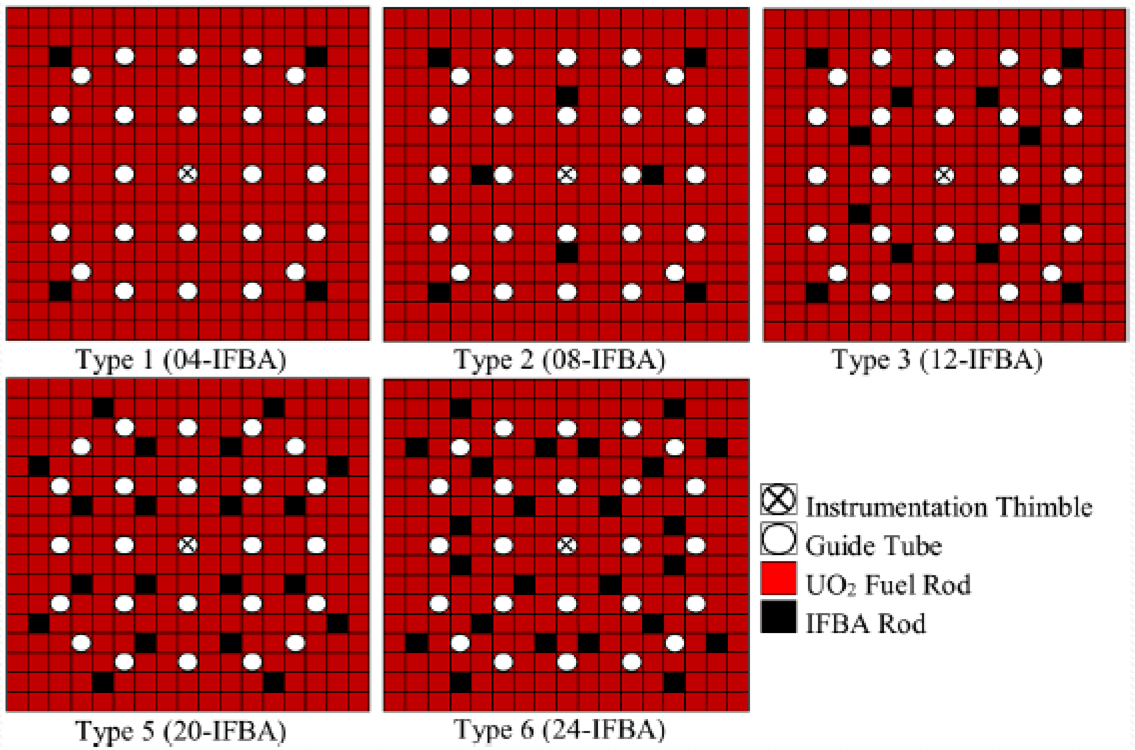


SMART CORE



			B1	B2	B1			
		B2	B5	B6	B5	B2		
	B2	B5	A3	A2	A3	B5	B2	
B1	B5	A3	A2	A3	A2	A3	B5	B1
B2	B6	A2	A3	A2	A3	A2	B6	B2
B1	B5	A3	A2	A3	A2	A3	B5	B1
	B2	B5	A3	A2	A3	B5	B2	
		B2	B5	B6	B5	B2		
			B1	B2	B1			

Assembly type	No. of Assemblies	Normal fuel enrichment (w/o 235U)	No. of normal fuel rods per assembly	No. of Gd fuel rods per assembly	Gd content (w/o Gd_2O_3)
A2	9	2.82	256	8	8.0
A3	12		252	12	8.0
B1	8	4.88	260	4	8.0
B2	12		256	8	8.0
B5	12		244	20	8.0
B6	4		240	24	8.0


Type 1 (04-IFBA)
Type 2 (08-IFBA)
Type 3 (12-IFBA)
Type 5 (20-IFBA)
Type 6 (24-IFBA)

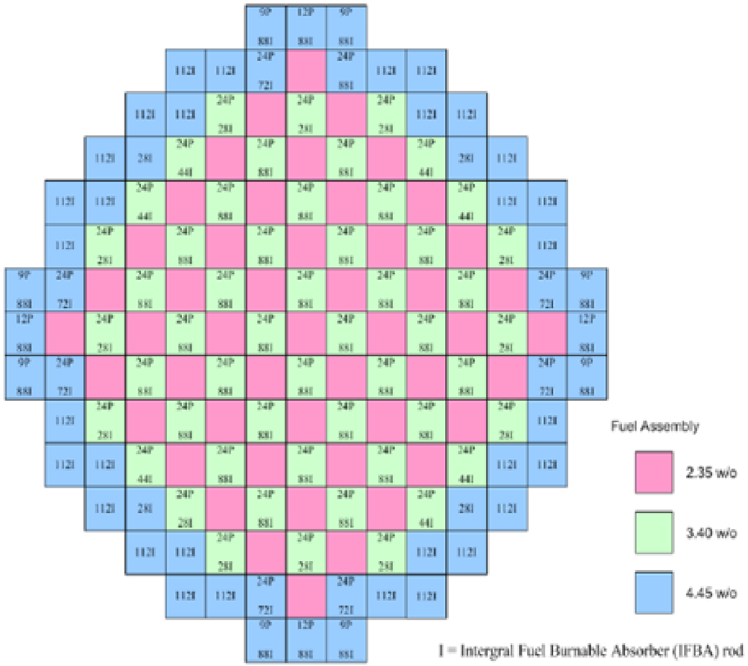
⊗ Instrumentation Thimble
○ Guide Tube
🟥 UO_2 Fuel Rod
■ IFBA Rod

Conversion of Advanced PWR for thorium utilization

Using of Thorium base fuel option in nuclear reactor has many advantages: the highest number of neutrons produced per neutron absorbed among all thermally fissile isotopes; neutron poison (Xenon and Samarium) production is 20% lower than other fissionable isotopes; reducing the radiotoxicity of the spent fuel, and non-proliferate. Besides the neutronic advantages, Thorium oxide (ThO_2) is relatively inert and does not oxidize further, unlike UO_2. It has higher thermal conductivity and lower thermal expansion coefficients compared to UO_2, as well as a much higher melting point (3300 °C). Also, given that at BOL Thorium could be used as a poison and during the reactor cycle as a fertile nuclide, it reduces the amount of burnable poison and extent the cycle life.

Feasibility to convert an advanced PWR from UO2 to a mixed U/ThO2 core(*Annals of. Nuclear. Energy* 102, 47–45/*The 26th International Conference Nuclear Energy for New Europe (NENE*), Bled-Slovenia, 2017

- AP 1000 reference reactor



						🟦 9P 88I	🟦 12P 88I	🟦 9P 88I						
				🟦 112I	🟦 112I	🟦 24P 72I	🟥	🟦 24P 88I	🟦 112I	🟦 112I				
			🟦 112I	🟦 112I	🟩 24P 28I	🟥	🟩 24P 28I	🟥	🟩 24P 28I	🟦 112I	🟦 112I			
		🟦 112I	🟦 28I	🟩 24P 44I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 44I	🟦 28I	🟦 112I		
	🟦 112I	🟦 112I	🟩 24P 44I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 44I	🟦 112I	🟦 112I	
	🟦 112I	🟩 24P 28I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 28I	🟦 112I	
🟦 9P 88I	🟦 24P 72I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟦 24P 72I	🟦 9P 88I
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	🟦 112I	🟩 24P 28I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 28I	🟦 112I	
	🟦 112I	🟦 112I	🟩 24P 44I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 44I	🟦 112I	🟦 112I	
		🟦 112I	🟦 28I	🟩 24P 28I	🟥	🟩 24P 88I	🟥	🟩 24P 88I	🟥	🟩 24P 44I	🟦 28I	🟦 112I		
			🟦 112I	🟦 112I	🟩 24P 28I	🟥	🟩 24P 28I	🟥	🟩 24P 28I	🟦 112I	🟦 112I			
				🟦 112I	🟦 112I	🟦 24P 72I	🟥	🟦 24P 72I	🟦 112I	🟦 112I				
						🟦 9P 88I	🟦 12P 88I	🟦 9P 88I						

Fuel Assembly

🟥 2.35 w/o

🟩 3.40 w/o

🟦 4.45 w/o

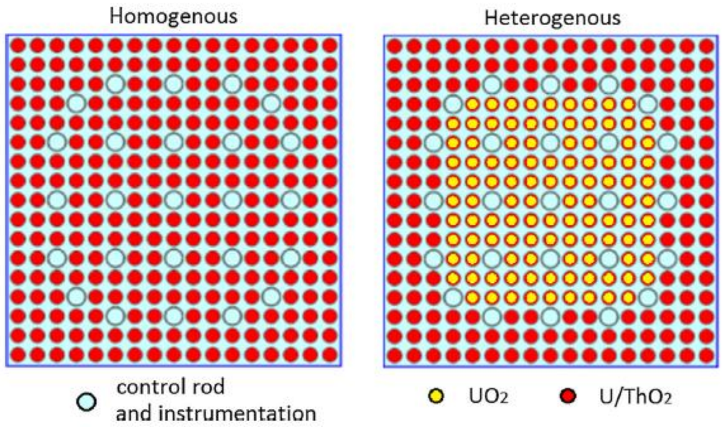
I = Intergral Fuel Burnable Absorber (IFBA) rod

CRITERIA

- Produce the maximum amount of fissile ^{233}U at end of cycle (EOC).
- Generate minimum amount of fissile plutonium to reduce long lived waste generation (an important sustainability criterion for nuclear power);
- Ensure that the maximum centre line fuel temperature and maximum linear power density do not exceed the values from the AP1000 reference core;
- Ensure that kinetics parameters and temperature coefficient of reactivity do not change significantly to maintain similar current AP1000 safety and transient behaviour;
- Ensure that the fuel cycle life is 18 months or longer. Discharge average burnup ~60 MWD/kgHM at equilibrium cycle.

Methodology
Parametric Studies

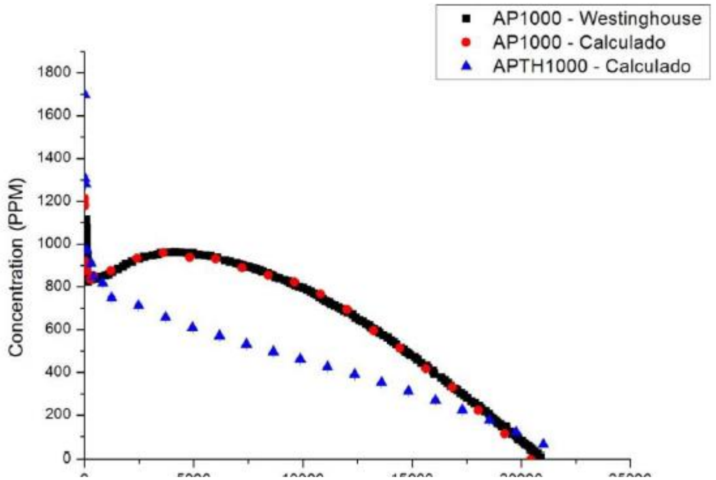
- First we qualify our calculation methodology(SERPENT/STH-MOX-Th) by reproducing the AP 1000 Design Control Document
- We select 20 cases(15 heterogeneous/5 homogeneous) with different mass proportion of U and Th, and LEU and perform calculation for all cases without considering any burnable poison.
- The results obtained for these 20 cases for the k_{eff} at BOC and EOC, conversion factor, β_{eff}, maximum linear power density, fuel centre line temperature, and mass of ^{233}U; ^{239}Pu, ^{241}Pu, were compared with the AP 1000 reference core without any burnup poison, in order to select those which would satisfy the criteria.

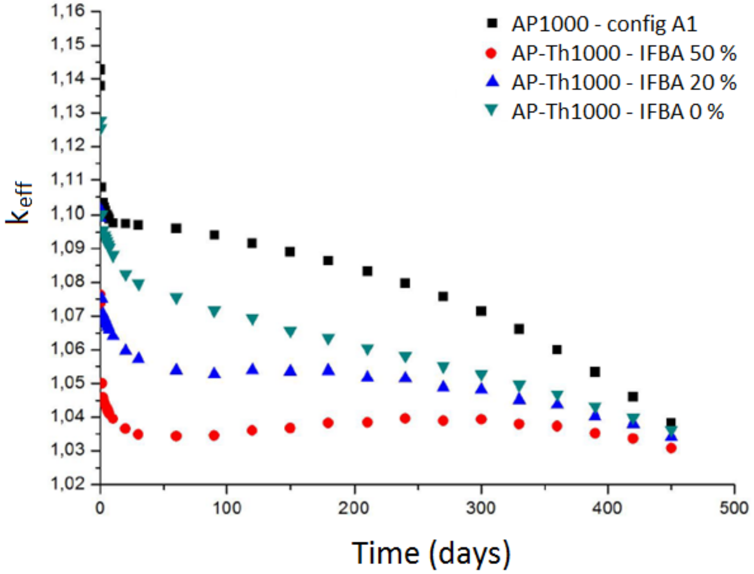


Confi-guration	Region 1 ($^{w}/_{o}$)				Region 2 ($^{w}/_{o}$)				Region 3 ($^{w}/_{o}$)			
Isotopes	^{232}Th	^{235}U	^{238}U	^{16}O	^{232}Th	^{235}U	^{238}U	^{16}O	^{232}Th	^{235}U	^{238}U	^{16}O
THOM-1	73.8	2.82	11.3	12.1	66.8	4.23	16.9	12.1	59.8	5.64	22.6	12.0
THOM-2	61.5	2.79	23.6	12.0	61.5	4.04	22.4	12.0	61.5	5.28	21.1	12.0
THOM-3	57.1	3.26	27.6	12.0	57.1	4.71	26.1	12.0	57.1	6.17	24.7	12.0
THOM-4	65.9	2.32	19.7	12.0	65.9	3.37	18.7	12.0	65.9	4.41	17.6	12.0
THOM-5	48.3	3.14	36.5	12.0	48.3	4.55	35.1	12.0	48.3	5.95	33.7	12.0

Results

- **The results obtained for these 20 cases for the k_{eff} at BOC and EOC, conversion factor, β_{eff}, maximum linear power density, fuel center line temperature, and mass of ^{233}U; ^{239}Pu, ^{241}Pu. These results showed that the configurations based on the heterogeneous concept presents the better reactor physics properties but the highest peak linear power densities. They were dismissed simply because of thermal hydraulic limits, i.e., high maximum center line fuel temperature. Among the configurations with EOC keff greater than 1.05000 the q'_{max} was always larger than the reference AP1000 value by 30–67%. For the homogeneous configurations, most of them satisfied the criteria's, however the configuration with three different mass proportion zones, the first containing (32wt% UO_2-68wt%ThO_2); the second with (24wt% UO_2-76wt% ThO_2), and the third with (20wt% UO_2-wt80% ThO_2), using ^{235}U LEU (20 wt%), and corresponding with the 3 enrichment zones of the AP 1000 (4.45 wt%; 3.40 wt%; 2.35 wt%).was the one which produces more ^{233}U at EOC, as well as a lower linear power density, and therefore it was the one choose to be the converted core of AP 1000.**

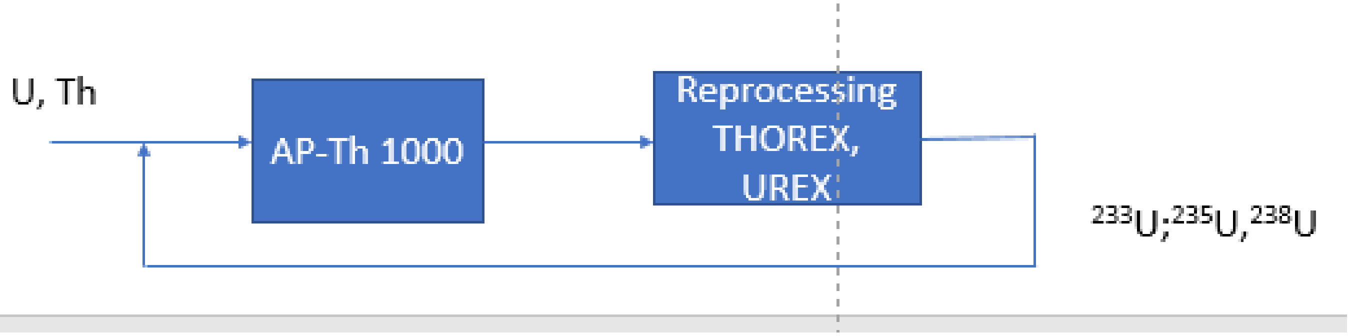




Conclusions

Big Reactor

- From these results, we may conclude that it is feasibly to convert the AP 1000, to use U/Th oxide without any change in the plant, only changing the fuel pellets, with advantages such as a lower maximum linear heat density, eliminating the IFBA, reducing the soluble boron concentration, and even the possibility of an extended discharge burnup (>60,000 MWD/MTHM), although the in-core fuel management is ongoing. Although regarding the natural uranium resource consume is a disadvantage, in OTC fuel cycle, since AP-Th 1000 consumes more uranium, we note that by optimizing the production of ^{233}U, we expected that the concept could be used as producer of ^{233}U, and therefore the first step in a closed U/Th fuel cycle.



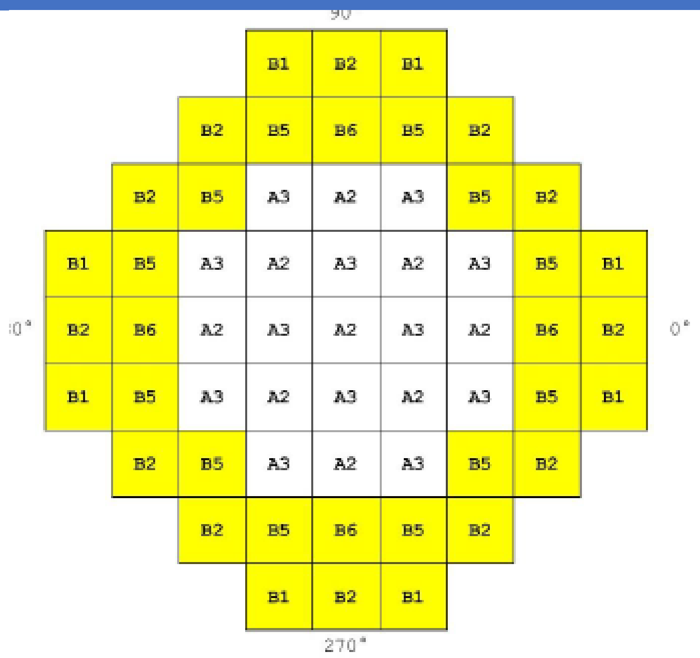
U, Th

AP-Th 1000

Reprocessing THOREX, UREX

$^{233}U;^{235}U,^{238}U$

Small Modular Reactors- The feasibility to convert SMART for using (U-Th)O_2 (Annals of Nuclear Energy, 120, 422–430, 2018).



			B1	B2	B1			
		B2	B5	B6	B5	B2		
	B2	B5	A3	A2	A3	B5	B2	
B1	B5	A3	A2	A3	A2	A3	B5	B1
B2	B6	A2	A3	A2	A3	A2	B6	B2
B1	B5	A3	A2	A3	A2	A3	B5	B1
	B2	B5	A3	A2	A3	B5	B2	
		B2	B5	B6	B5	B2		
			B1	B2	B1			

Most of The SMRs have been designed to have long cycle, so they must use a lot of poisoning material in the BOC. From the point that Thorium can be used as a absorber in the BOC and also be used as a fertile material during the cycle, it seems to be a good option to use mixed (U-Th)O_2 as SMR's fuel

Criteria

- **All core geometry (all fuel, control, burnable absorber and instrument rod diameters and pitch) must be kept fixed**
- **^{235}U fuel rods must have lower enrichment than 5 w/o.**
- **Keep temperature coefficient of reactivity negative, and kinetics parameter(βeff)value, near to SMART reference core values.**
- **Keep the fuel cycle length at least 3 Years. Achieving the longer cycle length.**
- **Using the less amount of fixed burnable poison as well as less soluble boron as possible.**
- **Producing the less amount of plutonium than SMART reference core (to reduce long lived waste isotopes).**

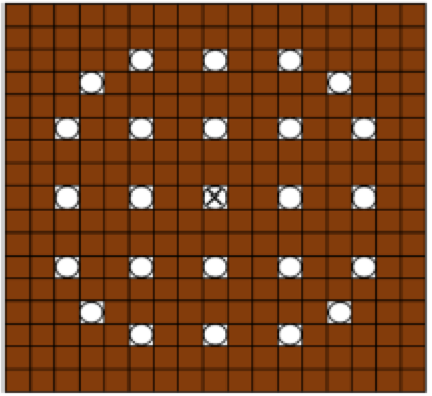
Calculation Methodology

- **All the neutronic calculation were performed by MCNP-CINDER90.**
- **Ensuring from the input data and geometry by comparing BOC results with standard safety analysis report (SSAR) of SMART core in different conditions according to the SMART SSAR.**
- **Choose a SMART core configuration for comparing different (U/Th)O2 core configurations with this reference. In the parametric study, both the reference SMART core and Th-U core were calculate first without any burn up poison.**
- **Proposing possible (U/Th)O2 core configurations for SMART core. For this purpose, two possible fuel assembly arrangement have been considered: homogenous mixed U/Th fuel assemblies and heterogeneous seed-blanket concept with Uranium fuel in the center and mixed U/Th in the outer region of fuel assembly.**
- **Performing the full core calculations at the beginning of cycle and during the cycle for different proposed (U/Th)O2 core configurations to check if the parameters met the criteria and assumptions.**
- **Select a potential configurations and then include the fixed burnup poison until we find the one which fill all the criteria imposed, by comparing with the reference core.**

Cases Studied in the Parametric Analysis

The Different mass proportion and Keff at BOC for homogeneous configuration

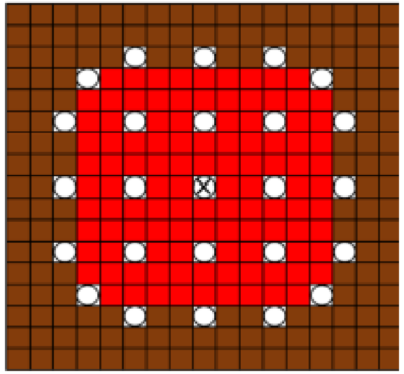
Configuration	^{232}Th (w/o)	^{238}U (w/o)	^{235}U (w/o)	O_2 (w/o)	K_{eff} at BOC
HomSMR-10	8.788	75.411	3.919	11.882	1.31079
HomSMR-15	13.182	71.222	3.701	11.895	1.28919
HomSMR-20	17.576	67.032	3.483	11.908	1.26758
HomSMR-25	21.970	62.843	3.266	11.921	1.24364
HomSMR-30	26.364	58.653	3.048	11.935	1.21500



🟫 (Th/U)O_2 Fuel
⊗ Instrumentation Thimble

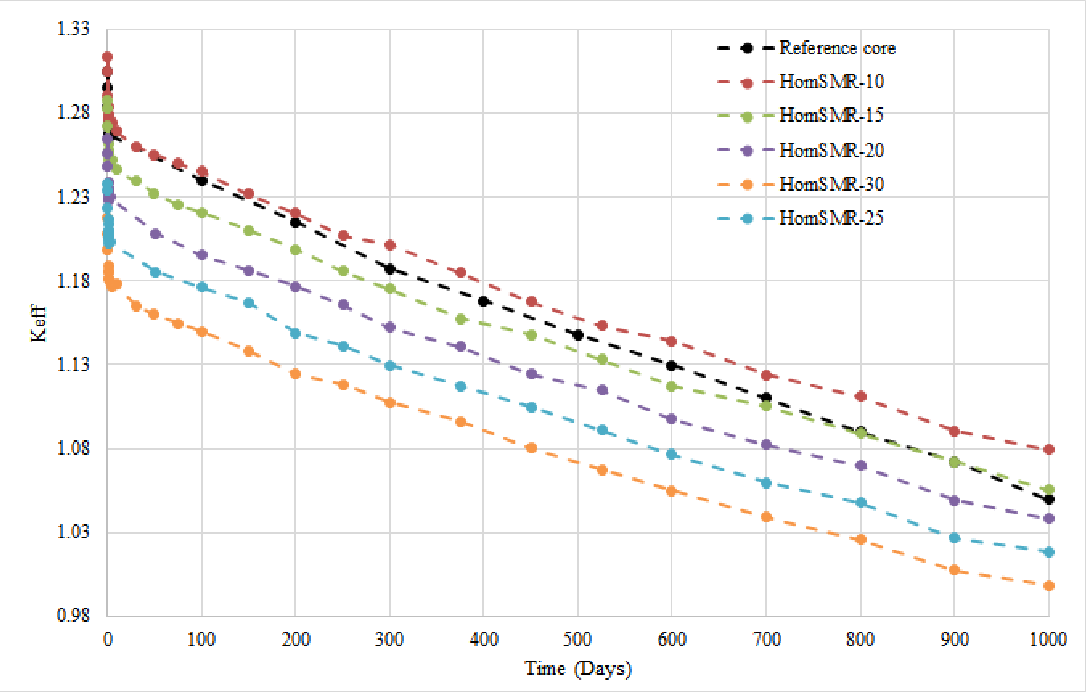
The Different mass proportion for heterogeneous configuration

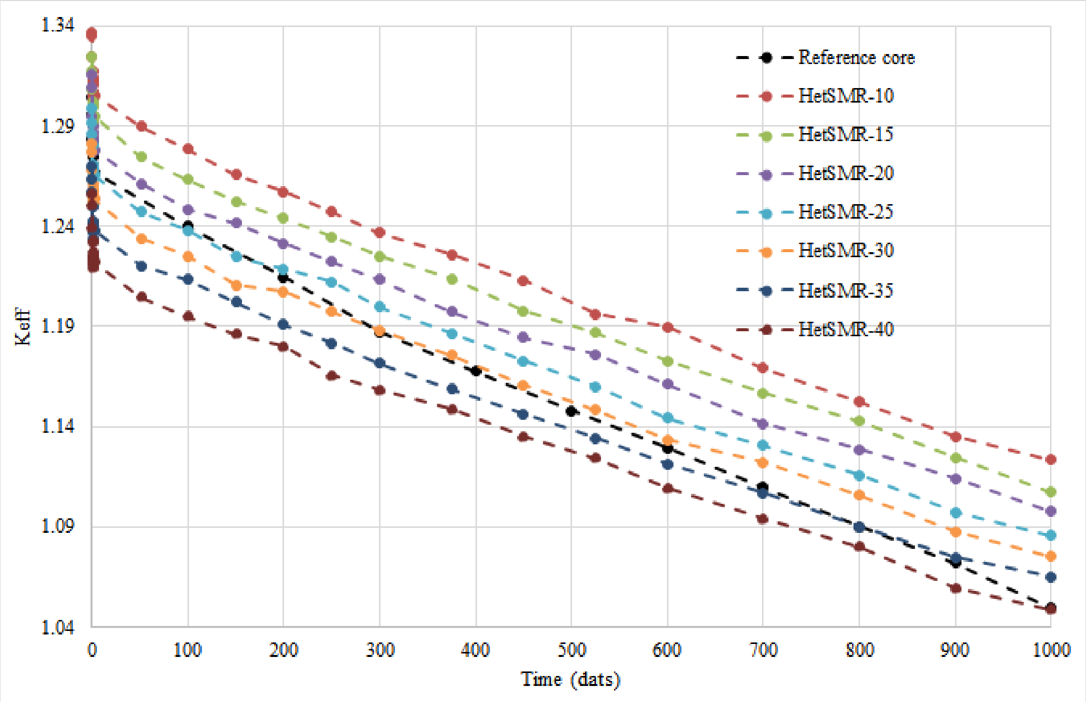
Configuration	^{232}Th (w/o)	^{238}U (w/o)	^{235}U (w/o)	O_2 (w/o)	K_{eff} at BOC
HetSMR-10	8.788	75.411	3.919	11.882	1.34078
HetSMR-15	13.182	71.222	3.701	11.895	1.32311
HetSMR-20	17.576	67.032	3.483	11.908	1.30963
HetSMR-25	21.970	62.843	3.266	11.921	1.29334
HetSMR-30	26.364	58.653	3.048	11.935	1.28667
HetSMR-35	30.758	54.4638	2.830	11.948	1.27228
HetSMR-40	35.152	50.2743	2.613	11.961	1.25620



🟥 UO_2 Fuel

Results for the parametric study- Without burn up poison





The burnup results for different mass proportion of homogeneous configurations.

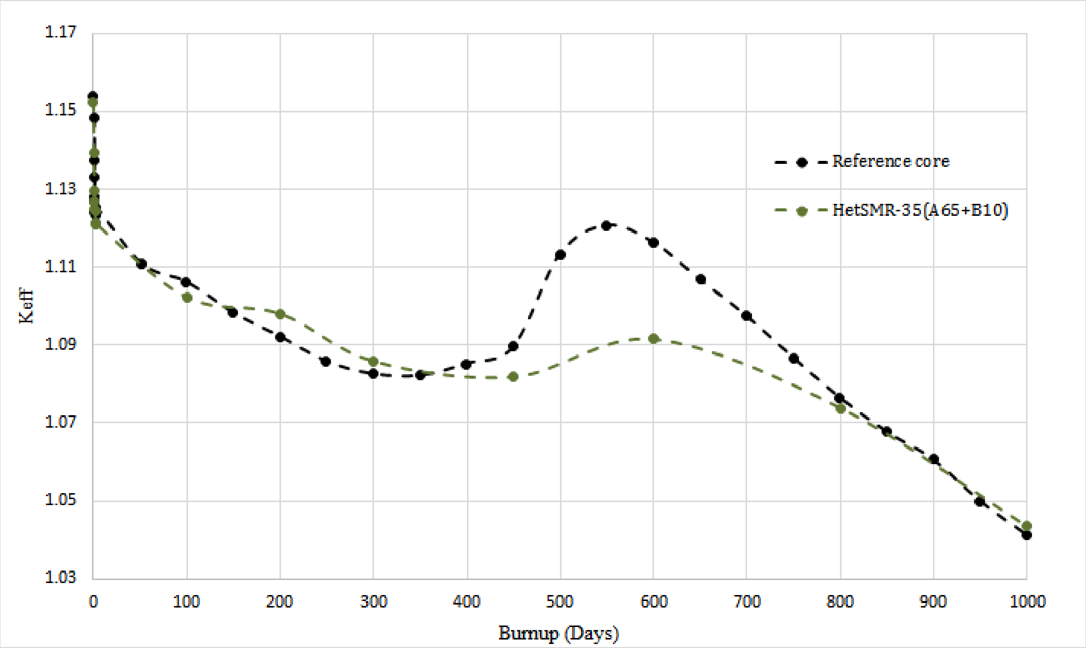
The burnup results for different mass proportion of heterogeneous configurations

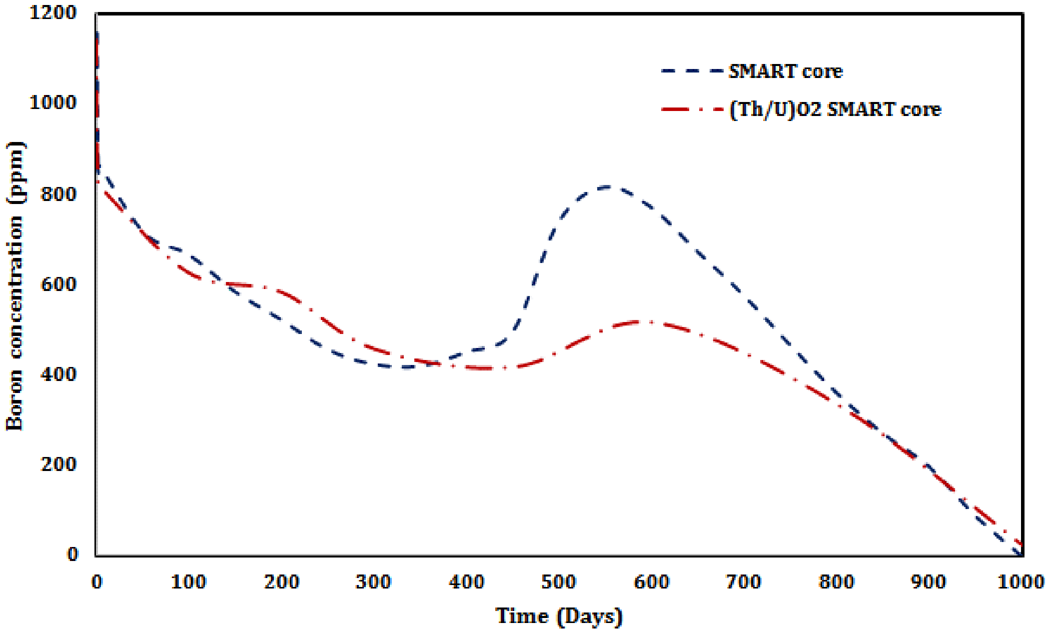
Comparison between reference SMART core and heterogeneous mixed oxide core.

Parameter	Reference Core		(Th-U) O_2*** Core	
	BOC*	EOC**	BOC*	EOC**
UO_2 Mass (kg)	16314	15752	12410	11946
^{235}U Mass (kg)	569	268	540	239
^{238}U Mass (kg)	13760	13550	10400	10230
ThO_2 Mass (kg)	0	0	3841	3771
Th Mass (kg)	0	0	3376	3312
^{239}Pu Mass (kg)	0	81	0	67
^{233}U Mass (kg)	0	0	0	38
Avg. Burnup (GWd/MTU)	-----	22.96	-----	23.06
Max. Burnup (GWd/MTU)	-----	24.67	-----	27.18

*** Beginning Of the Cycle of first core**
**** End Of the Cycle of first core**
***** 40% ThO_2 + 60% UO_2 for heterogeneous fuel assembly arrangement**

Final Results for the selected converted SMART core

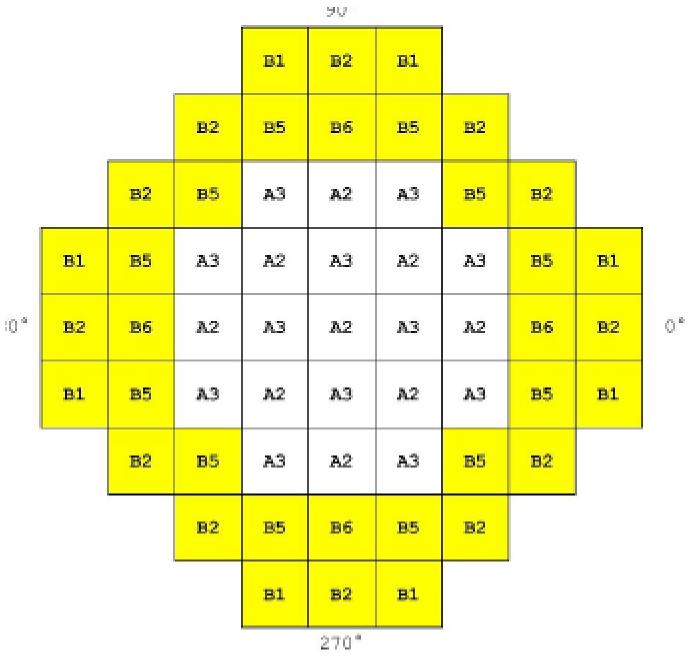




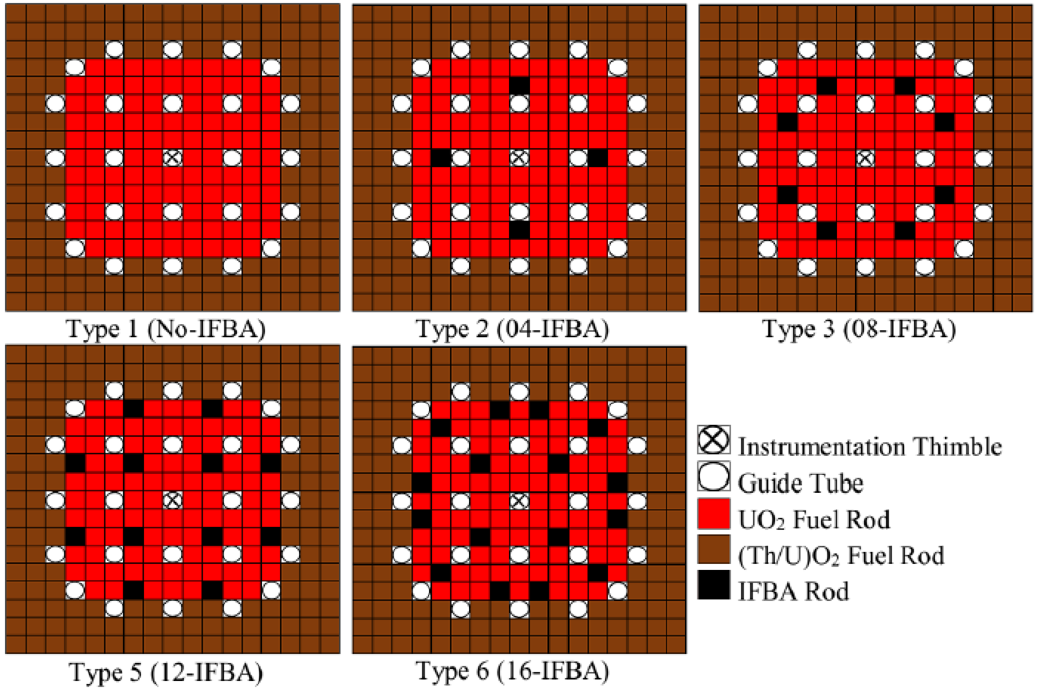
The burnup calculation of final selected (Th/U)O2 SMART core

Soluble boron changes for reference SMART and (Th/U)O2 SMART cores during the cycle.

(U-Th)O2 SMART CORE
Conclusions



			B1	B2	B1			
		B2	B5	B6	B5	B2		
	B2	B5	A3	A2	A3	B5	B2	
B1	B5	A3	A2	A3	A2	A3	B5	B1
B2	B6	A2	A3	A2	A3	A2	B6	B2
B1	B5	A3	A2	A3	A2	A3	B5	B1
	B2	B5	A3	A2	A3	B5	B2	
		B2	B5	B6	B5	B2		
			B1	B2	B1			



A mixed fuel core with 65% and 10% thorium respectively in the central and outer zone, has been proposed that has a longer cycle than reference core. In the reference core 680 burnable absorber rods have been used while in the proposed thorium mixed oxide core 388 burnable absorber rods have been used that means a large reducing in the amount of poison material. Also analysis of the soluble boron changes during the cycle shows that in the proposed core we can used less amount of soluble boron during the cycle.

https://sites.google.com/view/coauthor-mou/p%C3%A1gina-inicial

THANK YOU(спасибо)
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