Comprehensive Study of Lattice Cell Calculations for Thorium Based Fuel Cycle in Light Water Reactors Using SRAC Code

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The designers of the innovative reactors have proposed a number of approaches to increasing resource efficiency . Adding thorium, a fertile material, to the fuel is considered in this report. Under this approach, a large portion of the reactor output is produced by fissioning of the ^{233}U resulting from neutron capture by thorium, which results in reduced requirements for naturally-occurring fissile uranium (^{235}U). The proliferation potential of the light water reactor fuel cycle may be significantly reduced by utilization of thorium as a fertile component of the nuclear fuel.

The concept of using Th-^{233}U as fuel has been applied to an existing LWR design as compare with another fuel cycles (UO2 and MOX). SRAC code is extensive used to investigate the lattice cell problem.

1. Introduction.

Nuclear fuels used in reactors can be ^{235}U, ^{239}Pu and/or ^{233}U. The content of natural uranium contains 99.3% ^{238}U, 0.7% ^{235}U. The fuel irradiated in conventional light water reactors must be enriched from 2 to 4% ^{235}U to maintain nuclear fission chain reaction by using light water as the moderator and coolant. ^{239}Pu can be produced from fertile nuclide ^{238}U, while ^{233}U produced from ^{232}Th. Thorium is much more abundant in the earth's crust than uranium and the need of Pu burning from existing Pu stokpiles make the thorium based fuel cycle is widely considered for many decades.

Thorium like uranium can be used as fuel in nuclear reactors though thorium is not fissile material, but ^{232}Th is capable to capture slow neutrons to form ^{233}U, a fissionable isotope. Thus, thorium based fuel cycle can be used in all proven reactor types(1).

^{233}U produced from ^{232}Th in the neutronics point of view is one of the best isotope in the fissionable isotopes. In all energy range, neutron fission yield ratio (η) and the number of neutron absorbed are higher than those of ^{235}U and ^{239}Pu, so that ^{233}U could be used as fuel for many kind of reactor.

Thorium oxide ThO_2 has greater stability and can be used with high temperature, longer durability due to its melting point of 3050^0C (UO_2 : 2700 - 2800^0C) that expected to gain high burn-up.

The reactor fuelled by thorium will not reach critical but it can use a mixed core as the *seed-and-blanket* concept. ^{233}U would be produced which in turn fuel either the initial reactor. This feature is expected to be used to consume a large plutonium stockpiles today.

One of the advantages of ^{233}U as compare with ^{235}U and ^{239}Pu is that the higher neutron emitted yield when one neutron absorbed. The ^{235}U or ^{239}Pu are used to breed fissionable isotope from thorium. ^{232}Th absorbs neutron to become ^{233}Th and then decay to ^{233}Pa and finally to ^{233}U by decay chain:

$$
\begin{aligned}
&{}^{232}_{90}Th + {}^{1}_{0}n \rightarrow {}^{233*}_{90}Th \rightarrow {}^{233}_{90}Th + \gamma_c \\
&{}^{233}_{90}Th \rightarrow {}^{233}_{91}Pa + {}^{0}_{-1}\beta + \gamma_d + \nu \\
&{}^{233}_{91}Pa \rightarrow {}^{233}_{92}U + {}^{0}_{-1}\beta + \gamma_d + \nu
\end{aligned}
$$

The fuel is irradiated in the reactor core, in the back end of fuel cycle ^{233}U can be extracted from thorium and reused as fuel to make a close cycle. In this study, from reactor physics calculation aspect, our work focuses on estimation of nuclear fuel conversion of ^{233}U and those of uranium or MOX fuel cycles.

Capture cross section of ^{232}Th and capture and fission cross sections of ^{233}U give the fuel conversion ratio. The ratio of the number of fissionable nuclei produced from fertile material to the number of fissionable nuclei consumed in fission and non-fission reactions. It is given by:

$$N^{Fer}\sigma_c^{Fer} = N^{Fis}(\sigma_c^{Fis} + \sigma_f^{Fis})$$

Thus, ratio of fissionable content and fertile content in the fuel can be defined by:

$$\frac{N^{Fis}}{N^{Fer}} = \frac{\sigma_c^{Fer}}{\sigma_f^{Fis} + \sigma_c^{Fis}}$$

In thorium based fuel cycle, ratio of cross sections $\frac{\sigma_c^{Fer}}{\sigma_f^{Fis} + \sigma_c^{Fis}}$ identifies the capability of reproducing of ^{233}U fuel during the fuel irradiated in the reactor core.

For a purpose of proving the advantages of the thorium fuel cycle, the preliminary reactivity calculations were performed for lattices of fuel rods containing ThO_2 and $(Th,U)O_2$ as well as UO_2 and MOX. The reactor would be water cooled and retains all design features of a LWR.

2. Lattice cell calculations with LWRs.

The lattice cell of LWRs has a pin cell formed a square lattice as in Figure 1. The geometry parameters are in Table 1.

Table 1: Lattice cell parameters of LWRs.

Parameters	Material (temperature)	PWR	BWR
R1(mm)	Fuel (900 K)	4.096	4.12
R2(mm)	Clad (600 K)	4.75	4.76
L(mm)	Water (600 K)	12.6	12.65

From physics calculation aspect for lattice cell problem, the difference between PWR and BWR is that the coolant in PWR is not boil while in BWR the vapor content can be up to 40% in normal operation. The content of UO_2 3% -ThO_2 97% is used for Thorium fuel pin and UO_2 4% used for PWR and BWR pin cell calculations.

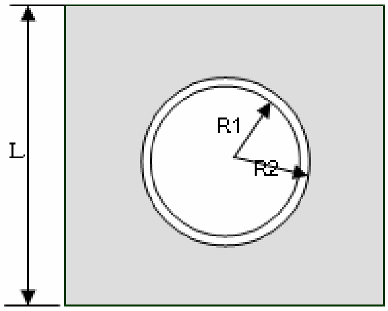

Figure 1: Lattice cell configuration of LWRs.

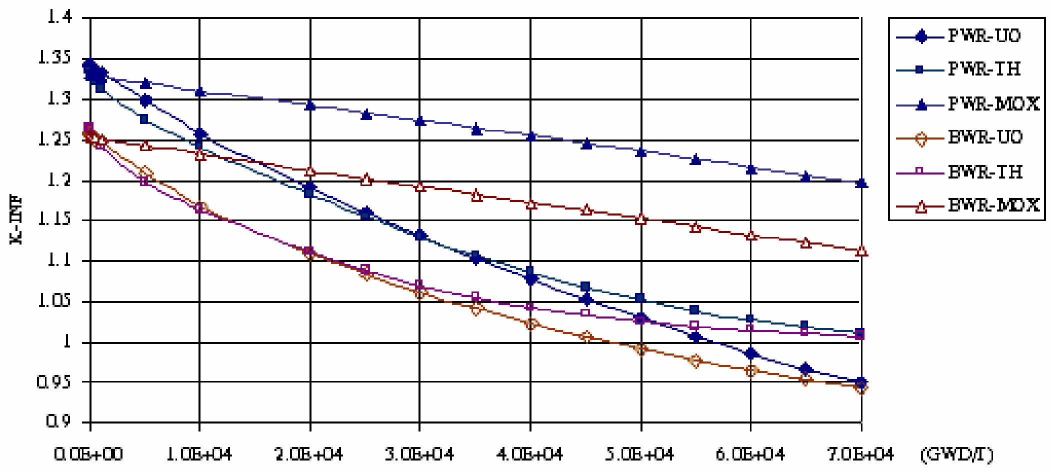

Figure 2: K-inf vs. Fuel Burn-up.

The variation of multiplication factor K-inf on fuel burn-up is presented in Figure 2. MOX and Th/^{233}U fuel can be burn up to 60GWd/T, while UO_2 fuel can be reach maximum at 35GWd/T – the average burn-up of present LWRs.

3. Estimate of fuel conversion factor.

With UO_2 and MOX fuels the conversion ratio is in the range of 0.5 to 0.7. Especially in MOX fuel, due to the main fission isotope is ^{239}Pu so that the conversion factor is not so high, while the ^{232}Th/^{233}U fuel it is much higher as ^{233}U is breeded during fuel irradiation in the core, the value obviously is greater than 1. The Figure 3 illustrates the variance of conversion factor by fuel burn-up of three fuel cycles.

It should be noted that if the UO_2/MOX fuels are used in combination with Th/^{233}U in a certain configuration of the core, the fuel conversion ratio would be improved, it will make the fuel burn-up more higher and save the ^{235}U fuel as well as the good option for consumption of plutonium.

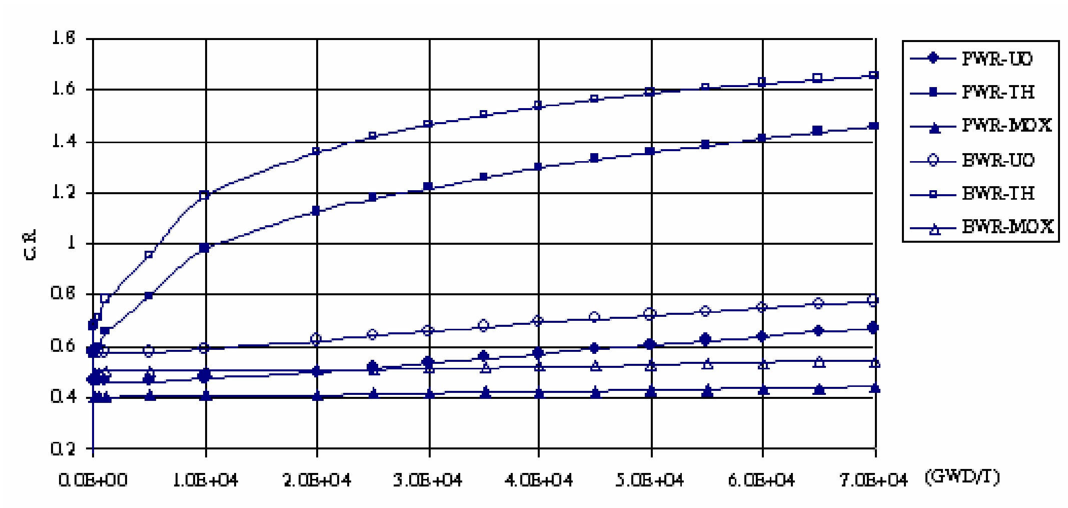

Figure 3: Conversion ratio (C.R) vs. Burn-up.

Further, from Table 2 we can see that the ^{239}Pu content produced from Th/^{233}U cycle is much less than those formed in UO_2 or MOX fuel cycles. This is also an advantage of thorium based fuel cycle as plutonium can not be extracted during reprocessing.

Table 2: ^{239}Pu content in the fuel burn-up.

GWd/T	PWR			BWR		
	UO_2	Th-^{233}U	MOX	UO_2	Th-^{233}U	MOX
1.0E+02	3.725E-07	1.023E-09	6.737E-04	4.634E-07	1.101E-09	6.732E-04
5.0E+02	4.609E-06	1.347E-08	6.731E-04	5.697E-06	1.441E-08	6.732E-04
1.0E+03	1.058E-05	3.180E-08	6.720E-04	1.304E-05	3.375E-08	6.740E-04
5.0E+03	4.884E-05	1.542E-07	6.712E-04	5.974E-05	1.541E-07	6.803E-04
1.0E+04	8.198E-05	2.476E-07	6.650E-04	1.022E-04	2.293E-07	6.876E-04
2.0E+04	1.194E-04	3.231E-07	6.573E-04	1.553E-04	2.635E-07	7.005E-04
3.0E+04	1.392E-04	3.375E-07	6.341E-04	1.938E-04	2.447E-07	7.108E-04
4.0E+04	1.474E-04	3.648E-07	6.176E-04	2.195E-04	2.266E-07	7.187E-04
5.0E+04	1.495E-04	4.212E-07	6.005E-04	2.376E-04	2.187E-07	7.242E-04
6.0E+04	1.488E-04	5.017E-07	5.828E-04	2.512E-04	2.241E-07	7.274E-04
7.0E+04	1.471E-04	5.954E-07	5.646E-04	2.620E-04	2.439E-07	7.286E-04

In general, Th/^{233}U fuel is used in combination with UO_2 fuel or MOX in fuel assemblies. The practical use has been investigating in India and many modeling studies have also been applied to present exist designs as PWR, VVER, PHWR [(4-9)].

In this study, two kinds of fuel are combined into one fuel rod. The UO_2 fuel as seed is centered and surrounded by $Th/^{233}U$ fuel outside.

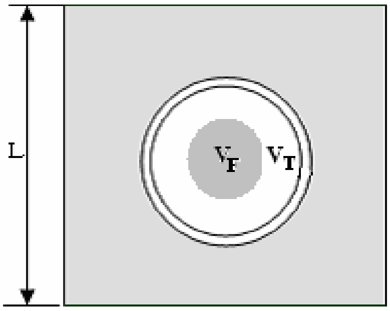

Figure 4: Two-layer fuel pin configuration.

The Figure 5 represents the dependence of multiplication factor K-inf and conversion ratio at the burn-up of 40 GWd/T by the volume ratio of UO_2 fuel alloy (V_F) and $Th/^{233}U$ fuel (V_T). When the UO_2 volume increases, multiplication will be increased and conversion ratio decreases. However, these parameters will have minor change in the range 1.5 and 2.5 of the ratio V_F/V_T values.

It should be noted that two-layered fuel rod may be one option in choosing the configurations of fuel assemblies beside well known configurations (4, 6, 7) that have been investigated. The detail investigations should be carried out to confirm the feasibility and applicability of this configuration.

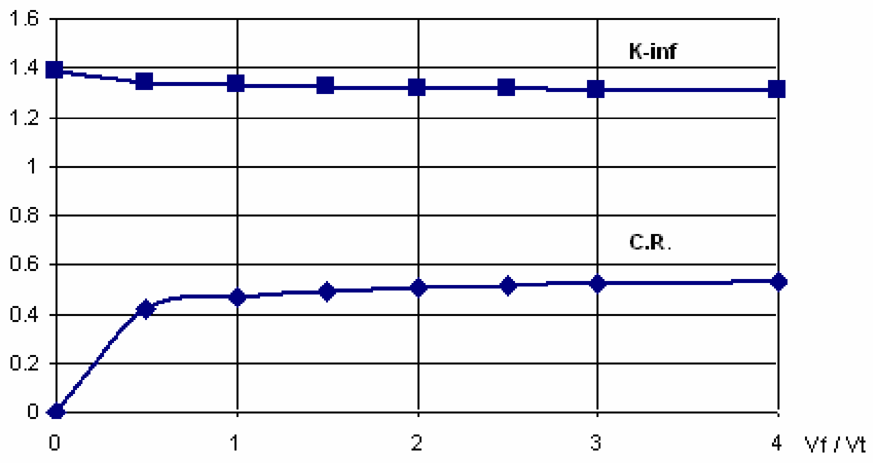

Figure 5: The multiplication factor K-inf and conversion ratio at burn-up of 40 GWd/T vs. Volume ratio of two-layer fuel rod.

4. Conclusion.

In the next several decades, the conventional LWRs based on uranium fuel cycle are still used. However, the other types of reactor are under extensive development, the typical reactors are

FBR, FBMR, HTGR etc. With the emphasize on transuranium and MA transmutation, the Th/^{233}U fuel cycle with the important advantages:

+ Contribute into burning of plutonium stockpiles, and ^{239}Pu produced by this fuel cycle is much less than MOX or UO_2 fuel.
+ High radioactive waste with large lifetime is less than other fuel cycles.
+ High fuel burn-up.
+ Used for high temperature reactors (HTR).
+ And sustainable as compare with limited uranium resource.

It will definitely be one of the remarkable options for nuclear fuel cycle in the future.

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