Harnessing Thorium for Clean Energy Future: Challenges Ahead*

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Abstract

Resolution of conflict between growing energy needs and threat of climate change necessitates a rapid transition to non-fossil energy sources of which nuclear energy is an essential key component. For a country like India which is endowed with abundant Thorium resources and only modest Uranium resources, harnessing Thorium for her energy needs has been a key development objective. Even for other countries, Thorium presents an attractive nuclear energy alternative that has the advantage of greater safety and larger resource base as well as higher proliferation resistance. While the optimised solution for harnessing Thorium over the long term could take time, there are opportunities to get started with Thorium almost immediately using established nuclear power reactor technologies and address some of the barriers to growth of nuclear energy utilising the advantages that Thorium can offer. This would also enable scaling up our experience with Thorium and facilitate transition from Uranium to Thorium at the contemporary scale of operation whenever such a change is contemplated.

Introduction

"International Energy Outlook 2013" has projected the growth of world energy consumption from 524 quadrillion BTUs to 820 quadrillion BTUs between the years 2010 to 2040. This represents a rise of around 54%. Most of this growth is expected to take place in non-OECD countries. During the same period, the relative share of non-fossil (renewable + nuclear) energy was assessed to be increasing from 16.5% to 21.4% only. This would correspond to an increase in CO_2 emission by around 40%[+]. It is thus clear that deployment of nuclear energy would need to be accelerated, both in terms of non-fossil energy source in the grid as well as to have a reasonable share of base load generation using non-fossil energy. The reality is however different. Nuclear power generation capacity is growing but rather slowly. This is because of the barriers that exist in smoother deployment of new nuclear power. Thorium has a number of features that can soften some of these barriers and facilitate growth of nuclear power. We also need to recognise that globally, Thorium is 3 to 4 times more abundant as compared to Uranium.

+ Even after the historic agreement at Paris in December 2015 and INDCs announced by all countries, the target of limiting global temperature rise to within 2^0C above pre-industrial level is still eluding us.

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As far as India is concerned, as against a minimum annual per capita energy use of around 2500 kgoe that would be necessary to support a high human development index similar to what obtains in advanced countries, the current level of energy use is just about a fourth. Thus, our current energy use of 0.82Btoe would need to go up to a level of around 4.125Btoe, taking into account likely increase in population. India's total primary (coal, oil and gas) energy resource is estimated at around 361.8Btoe. In reality the actual mineable resource might be much less. There is thus a significant energy sustainability issue over and above the threat of climate change that is involved as far as the use of fossil energy available on Indian land mass is concerned. Burgeoning energy import bill particularly in the context of oil and gas is already a matter of serious worry that is expected to become worse in years to come. Clearly this demands serious efforts to shift India's energy basket to domestic non-fossil energy. Luckily, the only two energy resources that are available on Indian land mass and would be sufficient to sustainably meet India's long term energy demands are Solar and Thorium. All other resources, though very important in the short run, would be far from being adequate in the long run. Use of both Solar and Thorium for energy production does not lead to any significant CO_2 emissions. Further Solar and Thorium are complimentary energy resources – intermittent v/s base load generation, diffused v/s concentrated energy source etc. suggesting that both would be needed.

Going Forward

Thorium as it occurs in nature does not have any fissile component. To start energy production from Thorium therefore, one needs to use other available fissile materials or neutron irradiation platforms. Further, the scale at which Thorium utilisation can be pursued for energy production, pretty much depends on the prior inventory of fissile materials or capacity of irradiation platforms for conversion of Thorium. Thorium, while its utilisation can be designed to be in self-sustaining mode, would not support very significant growth through breeding by itself. This has been the basis of India's sequential three stage nuclear power programme where large scale utilisation of Thorium, even with modest availability of Uranium, has been the long-term core objective from day one. Development of technologies related to Thorium utilisation have thus been steadily pursued in India hand in hand with the development of the first two stages involving thermal and fast breeder reactors respectively. For the world, at large however, the scarcity of Uranium is not yet in sight and significant nuclear reactor capacity exists already. Availability of Uranium or the capacity of platforms for irradiation of Thorium is thus not a constraint. There is thus an opportunity to start utilising Thorium immediately provided the advantages of doing so can be clearly seen.

According to WNA data, there are some 440 nuclear power reactors operating in 31 countries with a combined capacity of over 385 GWe. Over 60 power reactors corresponding to around 15% additional capacity are currently being constructed in 13 countries. Further over 160 power reactors with a total net capacity of some 182 GWe (close to half the present capacity) are planned and over 300 more are proposed.

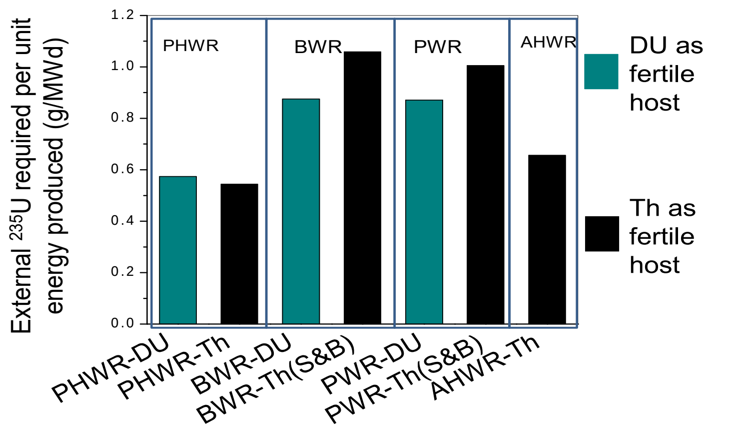
Clearly, the projected growth of nuclear generation capacity is way short of the need for non-fossil capacity addition to contain global warming. At this stage, we need to recognise that growth of additional capacity is expected primarily in countries like China, India, Korea, Russia and United States. Also, there are a number of potentially emerging nuclear countries which need additional power generation capacity to support their economic growth. Option of nuclear power is under their active consideration. Experience so far suggests that the interest of emerging nuclear countries does not fully translate into actual deployment perhaps as a result of their perceived concerns. Their concerns primarily relate to 1) unmanageable liability that can arise out of large scale displacement in the event of a major nuclear accident, 2) safety, security and waste disposal issues over short and long term related to spent fuel management, 3) concerns over potential for diversion of fissile materials for malevolent purposes, 4) large capital investments necessary with large size nuclear plants available on the market and 5) competitive unit energy cost.

Satisfactory resolution of these issues would go a long way in facilitating a faster growth of nuclear power worldwide. Thorium can indeed play an important role here in softening the barriers to nuclear power deployment.[1] Further, Thorium presents a much larger clean non-fossil energy potential available for large scale power generation in conjunction with large accumulation of fissile inventory in several countries. This at the same time also alleviates concerns related to such an accumulation through its safe and secure elimination. We will discuss these aspects in subsequent paragraphs.

Thorium, an efficient fertile host

Heavy water reactors offer better economy in use of fissile material over light water reactors, with thorium as the fertile host

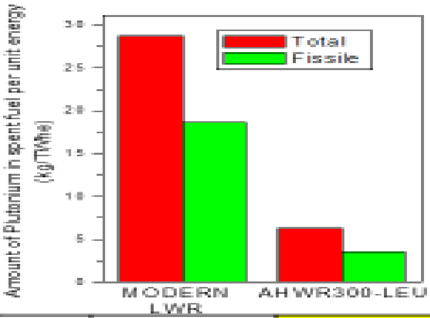
Figure: Courtesy colleagues in RDDG, BARC



In early stages of nuclear technology development, burn up realisable in water reactors was quite limited. Under such conditions, use of Thorium as fertile material in fuels meant the need for additional fissile material, since the benefit of in-situ bred ^{233}U was not sufficient enough to compensate for the heavy absorption of neutrons in Thorium. Efficiency of fissile material use under such conditions was thus lower as compared to standard Uranium fuel and there was no incentive to use Thorium as fertile host. With the improvements in nuclear fuel technology, things have changed. Today burn up in excess of 60,000 MWd/t is quite common in water reactors. At this level of burn up a much larger share of energy can be obtained from fission of ^{233}U bred in situ, leveraging efficient conversion of fertile to fissile material in Thorium. Thus, in contrast to earlier times, today the fissile material use efficiency with ^{232}Th as fertile host is comparable with ^{238}U. While this is generally true with all reactor types, Heavy Water Reactors, known for their superior neutron economy, in fact deliver better fissile material use efficiency with Thorium as fertile host. There is thus incentive for use of Thorium in current generation water reactors to derive benefits without any significant compromise on energy output from a given quantity of available fissile material (^{235}U).

Softening barriers to nuclear power deployment leveraging special features of Thorium

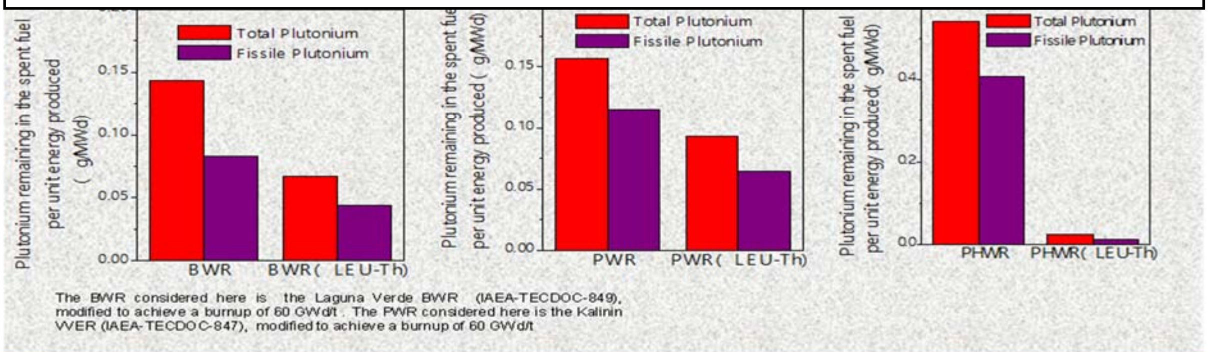
Accidents like Chernobyl and Fukushima have underscored the need to minimise the impact of a severe accident in public domain. This is basically a matter of reactor design that ensures absence of core heat up even under conditions of multiple equipment failures. However, use of Thorium enables appropriate reactor core behaviour to facilitate such a performance. Indian Advanced Heavy Water Reactor is an example of how this can be achieved.[2] This reactor is an innovative configuration using present day technologies and grossly reduces impact in public domain and offers far better resistance to insider/outsider malevolent acts. Design and development of this reactor is more or less complete and is ready for taking up construction. The front end as well as the back end of fuel cycle of AHWR 300 LEU version of this reactor fuelled by LEU+Thorium oxide fuel also offers a high degree of proliferation resistance. The design that has been presently worked out is for a 300 MWe capacity and is well suited to needs of smaller countries as also for countries where there are needs for marginal capacity addition.



^{238}Pu	3.50	%	9.54	%
^{239}Pu	51.87	%	41.65	%
^{240}Pu	23.81	%	21.14	%
^{241}Pu	12.91	%	13.96	%
^{242}Pu	7.91	%	13.70	%
^{232}U	0.00	%	0.02	%
^{233}U	0.00	%	6.51	%
^{234}U	0.00	%	1.24	%
^{235}U	0.82	%	1.62	%
^{236}U	0.59	%	3.27	%
^{238}U	98.59	%	87.35	%

Significant reduction of proliferation risk can be realised with deployment of Thorium as fertile part of the fuel even in present day designs of water reactors that are currently in use. This gain is maximum in PHWRs. It is interesting to note that Indian PHWRs are available in a range of capacities (220 MWe to 700 MWe) to suit needs of individual countries with favourable economics as compared to other reactor designs in spite of the economy of scale. Adjustments in design would be necessary in fuel to cope with higher burn up and in reactivity control system in view of altered reactivity picture. This thus presents an interesting opportunity to smoothen one of the important barrier to large scale deployment of nuclear energy in newly emerging nuclear countries.

Reduction in proliferation risk with adoption of Thorium
in current design of water reactors Figure
: Courtesy colleagues in RDDG, BARC



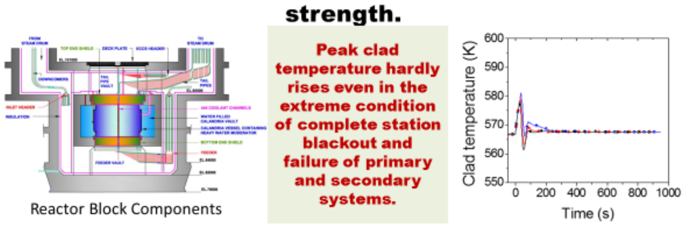
Closing of the fuel cycle is necessary for realisation of fuller energy potential energy available in Uranium and Thorium. It is this possibility that enables nuclear energy to offer a sustainable clean energy solution for the world at large. However, fear of diversion of separated fissile materials has resulted in many countries adopting open once through fuel cycle. Permanent disposal of used fuel coming out of nuclear reactors that have adopted once through fuel cycle has remained an unresolved issue and it is likely to remain so. In contrast the recycle option, while paving the way for consuming the fissile materials and produce additional energy, does leave some fear of possibility of diversion of fissile materials for malevolent purposes. Recycle option with Thorium however considerably reduces these fears because of inherent non- proliferation characteristics that get introduced in fissile materials in a Thorium based fuel cycle.

Even if a country decides against recycle for the time being, Thorium bearing spent fuel offers several advantages by way of greater stability and better thermo-physical and chemical properties besides comparable or better Uranium utilization as brought out earlier. At a later date the country could decide on differed recycle strategy. Either way the Thorium option enables a regime that is more secure from the risk of unanticipated diversion.

Way ahead

The need to cut down on carbon di oxide emission is becoming more urgent every passing day. The historic Paris agreement which brought about all countries of the world together to declare their respective INDCs is still short of limiting global temperature rise to below the target of 2^{o}C above the preindustrial levels. There is thus a need to further accelerate deployment of non-fossil energy. That inevitably means that nuclear energy must go hand in hand with Solar energy to maintain a balance in terms of base load generation. While there is a realisation about the importance of urgent growth of nuclear power, apprehensions remain. As explained earlier, Thorium can play an important role here. Strategies for harnessing Thorium for our clean energy future can thus be seen evolving in phases. In the short term, Thorium can be used in most of present day thermal reactor systems by incorporating it as the fertile part of fuel in place of ^{238}U with fissile part coming in the form of LEU with maximum permissible concentration (~20%). Fuel design would need to be rechecked and modified if necessary to sustain the highest possible burn up. Likewise, the reactivity control elements and refuelling pattern would need to be revised to remain within the permissible operational and safety limits. Clearly these changes are marginal but would allow considerable softening of barriers to deployment of nuclear energy particularly in the context of proliferation concerns. In the medium term one could innovatively reconfigure reactors using Thorium based on present day technologies to derive further advantage to minimise the impact in public domain in case of an unlikely accident as well as to enhance inherent security strength against external or internal malevolent acts. As mentioned earlier, AHWR 300 – LEU is a good example of this strategy. In the longer term one could see reactors designed specifically to exploit full potential of Thorium. These would need significant new technologies to be developed such as Molten Salt Reactors, High Temperature Reactors, Accelerator Driven Subcritical Reactor System etc. Such phased Thorium deployment strategy should enable enhanced deployment of nuclear energy in the nearer term averting the climate change threat and greater level of Thorium Utilisation in the longer term leading to greater sustainability with nuclear energy solution.

AHWR 300-LEU is a simple 300 MWe system fuelled with LEU-Thorium fuel, has advanced passive safety features, high degree of operator forgiving characteristics, no adverse impact in public domain, high proliferation resistance and inherent security strength.



AHWR300-LEU provides a robust design against external as well as internal threats, including insider malevolent acts. This feature contributes to strong security of the reactor through implementation of technological solutions.

Closing remarks

Despite awareness about impact of CO_2 emissions, imperatives of economy and development are leading to growth in fossil energy use and issues of sustainability. India is pursuing a three-stage nuclear power programme designed to achieve a large share of nuclear energy in the overall long term energy mix leveraging her vast Thorium resources. While this sequential nuclear energy development programme is inevitable in Indian context and has its own time frame for deployment of Thorium on a large scale, there are also opportunities for deployment of Thorium with current thermal reactor systems in the shorter term with a view to soften barriers to deployment of nuclear power and address the global challenge posed by climate change threat. Indian experience with PHWRs and AHWR can be of advantage to world at large in this context.

References

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