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Comparison for thorium fuel cycle facilities of two different capacities for implementation of safeguards

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HIGHLIGHTS

- Facilities for implementation of safeguards for thorium fuel cycle have been compared.
- Two concepts have been compared.
- In one concept, the facilities are designed in hub and spoke concept.
- In second concept the facilities are designed as self-contained concept.
- The comparison is done on a number of factors, which affect safeguardability and proliferation resistance.

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ABSTRACT

Thorium based nuclear fuel cycle has many attractive features, its inherent proliferation resistance being one of them. This is due to the presence of high energy gamma emitting daughter products of U^{232} associated with U^{233}. This high energy gamma radiation also poses challenges in nuclear material accounting. A typical thorium fuel cycle facility has a number of plants including a fuel fabrication plant for initial and equilibrium core, a reprocessed U^{233} fuel fabrication plant, a reprocessing plant, a fuel assembly/disassembly plant and associated waste handling and management plants. A thorium fuel cycle facility can be set up to serve reactors at a site. Alternatively, one can follow a hub and spoke approach with a large thorium fuel cycle facility acting as a hub, catering to the requirements of reactors at several sites as spokes. These two concepts have their respective merits and shortcomings in terms of engineering and economics. The present paper is aimed at comparing the merits and challenges for implementation of safeguards on the two concepts viz. a large fuel cycle hub catering to reactors at several sites versus a small fuel cycle facility dedicated to reactors at a single site.

1. Introduction

Thorium based fuel cycle has many advantages, including proliferation resistance. India is developing a thorium fuel cycle which consists of different plants for fuel fabrication, fuel reprocessing and fuel refabricaiton. A fuel cycle complex can be set up to serve reactors at one site. Alternatively, it can be designed in a hub and spoke approach, where one large thorium fuel cycle facility acts as hub. This caters to a number of reactors located at different sites. There are relative merits and shortcomings in the two concepts, from the viewpoint of proliferation resistance. These two concepts have been analysed from the consideration of safeguardability and proliferation resistance.

2. Thorium fuel cycle

Thorium is more abundant than uranium and is widely distributed in nature. During the early years of nuclear energy development, there was considerable interest in developing thorium fuel cycles. However, the interest in thorium fuel cycles ebbed due to improved availability of uranium. While countries like India never abandoned pursuing research and development on thorium systems, continually rising demand for energy has brought thorium back on the agenda of several nations. A reactor using thorium alone cannot achieve criticality and a driver fuel is needed to make reactor critical. Rapid advances in accelerator technology have made Accelerator Driven Systems based on thorium a possibility in near future. Overall, there is renewed interest in thorium fuel cycles (IAEA, 2005), as it offers benefits like

(a) Better thermo-physical properties like thermal conductivity ensuring better in-pile performance, and better chemical

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stability of ThO_2 as compared to UO_2 ensuring a more stable waste form.

(b) Lesser generation of long lived minor actinides and plutonium than the traditional uranium fuel cycle.
(c) Superior Pu incineration in $(Th–Pu)O_2$ fuel as compared to $(U–Pu)O_2$ (Grupepelaar and Schapira, 2000).
(d) Possibility of breeding even in thermal and epithermal flux environment in addition to fast neutron flux environment.
(e) Intrinsic proliferation resistance of U^{233} due to association with U^{232}, a high energy gamma emitter.

However, there are challenges in deployment of thorium fuel cycles like

(a) Higher melting point of ThO_2 leading to requirement of higher sintering temperatures in fuel fabrication.
(b) Difficulty of dissolution of ThO_2 due to being a chemically inert matrix.
(c) Need for developing remote and shielded facilities for U^{233} fuel fabrication due to presence of high gamma emission on account of U^{232}.

International efforts aimed at developing new fuel cycles, like Innovative Nuclear Reactors and Fuel Cycles Programme (INPRO) and Generation IV International Forum (GIF) include thorium fuel cycles (MSR, 2012). Due to its modest uranium reserves and vast thorium reserves, India has considerable interest in thorium and to realise energy security for its huge population, it has envisaged a three stage nuclear power programme for optimum utilisation of its vast thorium resources. India has been pursuing a closed fuel cycle approach so as to realize the full energy potential of its modest uranium and vast thorium reserves (Planning Commission, 2006). To achieve the objective of utilizing thorium for power production, several steps have already been taken and these include the following,

- Fabrication and irradiation of Th metal and ThO_2 pins in research reactors.
- Using thoria pins as blanket in the Indian fast breeder test reactor.
- Using fuel bundles having thoria pins in Indian PHWRs for neutron flux flattening in the initial core.
- Reprocessing of irradiated thoria pins to recover U^{233} and its refabrication as U^{233}–Al alloy for plate type fuel, which is being used for a research reactor KAMINI (Ganguly et al., 1991).
- Fabrication of experimental ($U–Pu–U^{233}$) mixed oxide pins, which are now undergoing irradiation in Indian fast breeder test reactor (Anantharaman et al., 2008).

Having thus obtained laboratory scale experience in handling of thorium, India has now launched design and development of an Advanced Heavy Water Reactor (AHWR) and gaining industrial scale experience in handling of thorium is one of several objectives of launching AHWR (Sinha and Kakodkar, 2006). This will eventually pave the way for large scale thorium exploitation. Two concepts of AHWR are being developed; one using ($Th–U^{235}$) and the other using (Th–Pu) mixed oxide fuel as the driver fuel for the initial and the equilibrium core. The irradiated fuel containing Pu and U^{233} will be separated by aqueous reprocessing and refabricated to make ($Th–U^{233}$) mixed oxide fuel. This will be used as fuel in the subsequent cycles. To gain experience, test pins of (Th–Pu) mixed oxide have been fabricated and irradiated in a research reactor. These pins have also undergone post irradiation examination for characterization and fuel behaviour assessment. India thus has experience in all aspects of thorium fuel cycle including fuel fabrication and its characterization, irradiation, reprocessing and re-fabrication.

India is also examining Molten salt breeder concept for thorium utilization, but the study presented in this paper confines to fuel cycle associated with AHWR or similar other concept that might emerge in the future.

A fuel cycle facility mainly consists of a fuel fabrication plant, fuel assembly/disassembly plant, fuel reprocessing plant, waste management plant, post irradiation examination unit, pool side inspection unit, nuclear material storage unit and common utilities and services required for all the plants and units. The first core of the reactor will be fuelled with fuel clusters of (Th–Pu) or ($Th–U^{235}$) oxide. The fresh fuel for initial and equilibrium core will be fabricated in the powder pellet type of glove box based plant in case of (Th–Pu) oxide fuel. ($Th–U^{235}$) oxide fuel does not require glove box facility. The present paper aims to analyse fuel cycle concepts for AHWR wherein initial core will be fuelled by (Th–Pu) oxide, which will be manufactured in a glove box type of facility. The fuel assembly made in the fuel assembly plant will be sent to fuel building in the reactor for loading in the core. The irradiated fuel from the reactor, after adequate cooling, will be transported to the fuel assembly plant, which will also have facilities for disassembly. The disassembly will be carried out in hot cells and/or underwater. The segregated fuel pins will then be sent to reprocessing plant, which will have different streams based on aqueous reprocessing. The product of the reprocessing plant will be sent to reconversion laboratory for conversion to oxide powders of Pu, U (reprocessed) and U^{233}. The oxide powders of reprocessed U, Pu and Th will be sent for storage and U^{233} oxide will be sent to refabrication plant. This refabrication plant is alpha tight hot cells based, due to the presence of high gamma radiation emitting from U^{232}. ($Th–U^{233}$) oxide fuel pins will then be sent to the assembly plant for fuel assembly formation in hot cells or underwater. The equilibrium core will consist of clusters having pins of (Th–Pu) MOX and ($Th–U^{233}$) MOX. These pins will finally be sent to the reactor for irradiation, thus closing the fuel cycle. The thorium fuel cycle poses great technological challenges in aqueous reprocessing of highly inert thoria fuel, remote fuel fabrication inside shielded hot-cells, assembly and disassembly under water and remote handling of highly radioactive fresh fuel.

It is envisaged that when India decides to set up thorium reactors, there will be many reactors at a site and several sites at different places over the country. Fuel cycle facilities can be arranged in various configurations. The configuration represented in Fig. 1 is for a small facility dedicated to reactors at a single site. Such a concept envisages several small sized fuel cycle facilities each associated with reactors located at different sites. This configuration will make a site self contained and is referred to as self-contained concept. Alternately, a large fuel cycle hub can be designed, which could cater to several thorium based reactors in the country (Fig. 2). This is referred to as hub and spoke concept. The dedicated small fuel cycle facilities will have lesser number of fabrication, reprocessing and waste handling lines, while the single large facility will have more number of such lines.

3. Safeguards considerations for fuel cycle facilities in the two configurations under study

Safeguards implementation in various plants of the fuel cycle facilities like fuel fabrication, reprocessing and refabrication is a challenging task (Yamamura et al., 2008; Bjonard et al., 2009) Decision to adopt a particular configuration for deployment of thorium fuelled reactors on a large scale with their associated fuel cycle systems will depend on a number of factors like engineering challenges, economics and power requirement of various regions of country. Safeguardability and proliferation resistance will also be two of the deciding criteria, since large amounts of nuclear material