Progress in Nuclear Energy xxx (2017) 1–15

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

The evolution of the Indian nuclear power programme

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A R T I C L E I N F O

Article history:
Received 13 June 2016
Received in revised form
18 January 2017
Accepted 23 February 2017
Available online xxx

Keywords:
Pressurised heavy water reactor
Prototype fast breeder reactor
Fuel cycle
Accelerator driven sub-critical system
Advanced heavy water reactor
Pressurised water reactor

A B S T R A C T

The strategy for growth of nuclear power in India was planned nearly sixty years ago, noting the rather small uranium and large thorium reserves in the country. This has prompted India to adopt the well-known three stage programme. The first stage is primarily based on the Pressurised Heavy Water Reactors (PHWRs). The evolution of technology of PHWRs is discussed in the first part of this paper. India has constructed eighteen PHWRs, has achieved impressive availability factors and some of these reactors have achieved annual capacity factors of nearly hundred percent in the recent past. Having installed a nuclear power generation capacity of 6780 MWe (4460 MWe from PHWRs, 2000 MWe from PWRs and 320 MWe from BWRs), India is now poised to launch a major expansion programme. This will be based on the increased availability of uranium from import and from the augmented domestic supply. In the immediate future, the nuclear power capacity will grow by installing a series of indigenous PHWRs in addition to light water reactors built under international civil nuclear cooperation agreements. The growth of nuclear capacity in this period is aimed at increasing the share of nuclear power in meeting the base-load demand of non-carbon electricity required for the rapid economic growth in the country.

India embarked on its second stage programme with the successful operation of a research reactor named Fast Breeder Test Reactor (FBTR). Based on the experience of FBTR and following the development of all the required enabling technologies in India, the Prototype Fast Breeder Reactor (PFBR) of 500 MWe (gross) capacity has been designed, constructed and is now at an advanced stage of commissioning. A large increase in the nuclear power generation capacity is envisaged through deployment of fast breeder reactors. These reactors will not only help in building up nuclear power capacity but also, in due course, enable conversion of thorium into fissile U^{233}, which will fuel the reactors in the third stage of India's nuclear programme. The adoption of the closed fuel cycle for both thermal and fast reactors has dual objectives: multiplying the fissile inventory by fertile to fissile conversion and reducing the burden of long lived radioactive waste-both being essential for attaining near sustainability of nuclear power.

India has designed an Advanced Heavy Water Reactor (AHWR). This reactor can use one of the following fuels:

(i) Low enriched uranium dioxide-thorium dioxide based mixed oxide (MOX) fuel primarily in once through mode.
(ii) Plutonium dioxide – thorium dioxide MOX fuel in the closed fuel cycle mode. Eventually when enough of U^{233} is generated the reactor can operate with the U^{233}– thorium MOX fuel.

A large number of passive safety features are incorporated in this design.

As a part of the long term objective of the development of Accelerator Driven Sub-critical Systems (ADSS), work on the development of high power linear accelerator has been initiated.

1. Introduction

India started its nuclear programme at a time when the industrial infrastructure in the country was at its infancy. There was no

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http://dx.doi.org/10.1016/j.pnucene.2017.02.008
0149-1970/

research base from where a coordinated and mission oriented technology development activity could be initiated. At that time research activities were essentially confined to a limited number of university departments where facilities for large scale experimentation were not available. Homi Bhabha who initiated the nuclear programme in India recognised the importance of basic research and training of professionals in the early phase of programme. Right from the beginning the Indian nuclear programme was driven by an ambition of maximising the use of indigenous technologies and raw materials. The results of geological survey indicated that while the uranium reserve in the country was quite limited, there existed a huge reserve of thorium (Bhabha and Prasad, 1958; Ramanna, 1987) in the monazite bearing areas on the long Indian coastline. In the 1950s, worldwide, there was an expectation that nuclear energy could meet a major part of world's energy requirement and could sustain the same for a long time (Lewis, 1972; The History of Nuclear Energy (2016)).

A modest uranium reserve and a large thorium resource in India led to the adoption of the three stage programme (Bhabha and Prasad, 1958; Kakodkar, 1998). The first stage is primarily based on the Pressurised Heavy Water Reactors (PHWRs), which use natural uranium dioxide as the fuel and heavy water as both moderator and coolant. Due to the excellent neutron economy, the energy extracted per tonne of mined uranium in PHWRs was known to be better than other thermal reactors. The selection of PHWRs was appropriate also from the considerations that isotope enrichment technology and the manufacturing infrastructure for large size pressure vessels were not available in the country at that point of time. In order to be self-sufficient, development of technologies related to the manufacturing of PHWR-fuel and the heavy water production, were taken up quite early in the programme.

The second stage is primarily aimed at providing the needed additional fissile materials for the required sustainable growth of the installed nuclear power capacity by converting fertile nuclides into fissile ones. Plutonium fuelled fast reactors, due to their associated high breeding ratio, were the best choice for the second stage. Keeping this in view a closed fuel cycle was chosen and work on reprocessing of the PHWR spent fuel was initiated quite early. The advantage of the closed fuel cycle towards achieving a significant reduction of the radiotoxic burden of nuclear waste was also recognised (Balu et al., 1998). With the installation of the Fast Breeder Test Reactor (FBTR) in 1985 India entered the second stage of its programme (Paranjape and Sundaram, 1985). With the experience gained in operating FBTR and in handling molten sodium, the Prototype Fast Breeder Reactor (PFBR) of a capacity 500 MWe (gross) was designed. The design and development of PFBR was done by IGCAR, with the help of major experimental facilities for design validation, the support of Indian academic and other research institutions for additional specialised computational and experimental research based inputs, and the support of Indian industry for the development of manufacturing technologies for special equipment. The reactor has been constructed and is now nearly ready for commissioning.

Large scale utilisation of thorium for nuclear power was envisaged in the third stage. Once the installed nuclear capacity reaches a desired level and an adequate inventory of fissile nuclides is accumulated India will be ready to launch the third stage reactors with the U^{233}-Th fuel cycle. Fission characteristics of U^{233} are such that breeding is possible in a wide spectrum of neutron energy from thermal to fast, though not as efficiently as Pu^{239} in the fast neutron spectrum (>1 MeV). Power generation capacity established at that point of time can be sustained over several centuries with the operation of U^{233}- thorium fuel cycle which also has the advantage of generating much less long-lived radioactive waste.

With the increased availability of uranium from augmented domestic and foreign sources (under the international civil nuclear cooperation), the scope of the first stage of the Indian nuclear programme has been extended to include Light Water Reactors (LWRs) of foreign as well as Indian designs, along with the Indian PHWRs. The latest generation of the Indian PHWRs is designed for 700 MWe (gross) capacity.

As the opening paper of this issue, the present paper gives a brief account of the technology evolution, which has happened over the last six decades. The papers which follow elaborate the course of development in different technology domains. The present paper is divided in different sections. Section - 2 deals with the setting up of R&D facilities including research reactors and creation of industrial scale infrastructure for production of nuclear fuel, heavy water and electronic control systems. Indian contributions to the development of PHWR technology, which are the mainstay of Indian nuclear power programme today, are discussed in section- 3. The development of fast reactors, which forms the second stage, is discussed in section - 4. A study on the evolving fuel cycle with PHWR – Light Water Reactors (LWR) – Fast reactors in tandem is discussed in section – 5.0. Long-term perspectives of nuclear energy and accelerator driven systems are discussed in section-6 and -7 respectively.

2. Setting up of R&D and industrial scale facilities

India's nuclear programme, initiated just after the country became an independent sovereign state, was based on the following fundamental principles: (a) It should be indigenous both in terms of technology and materials and (b) It should grow in a manner that a significant part of the energy demand of the country can be met from nuclear energy in the long run without adversely affecting the environment. A great visionary, Homi Bhabha created the blueprint of this programme which was initiated with the formation of Indian Atomic Energy Commission in 1948. Due emphasis was given to basic research, development of scientific manpower and a stepwise capacity building in nuclear technology and nuclear materials (Ramanna, 1987; Sundaram et al., 1998; Anderson, 2010).

In order to achieve self-sufficiency in nuclear technology a comprehensive research facility was created in Atomic Energy Establishment, Trombay (AEET), which was later renamed as Bhabha Atomic Research Centre (BARC) after Bhabha's demise in 1966. Research teams in all disciplines relevant for the development of the nuclear technology in its entirety were nucleated and nurtured-which included reactor physics and engineering, electronics and control, materials science and processing, health physics and safety engineering, chemical engineering and reprocessing technology apart from core science disciplines.

The importance of the development of human resources was recognised right from the inception of the Indian atomic energy establishment. The BARC Training School was established in 1957 to provide postgraduate education in nuclear science and engineering to a very select group of fresh graduates in basic sciences and relevant branches of engineering. This institution has turned out over 8000 professionals in Physics, Chemistry, and Biology and in different branches of Engineering. A great majority of scientists and engineers who have contributed to the development of nuclear technology in India are graduates of BARC Training School. The fact that lectures and laboratory training are provided by specialists in respective fields has been responsible for the high quality of the education. With the establishment of Homi Bhabha National Institute in 2006 the opportunities for continuing education and acquiring higher academic degrees for the researchers in institutions of the Department of Atomic Energy (DAE) have greatly enhanced.