Progress in Nuclear Energy xxx (2017) 1–18

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Nuclear fuel cycle - developments and challenges in fuel fabrication technology in India

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ARTICLE INFO

Article history:
Received 6 December 2016
Received in revised form
23 February 2017
Accepted 1 March 2017
Available online xxx

Keywords:
Nuclear fuel fabrication
PHWR
Boiling water reactor (BWR)
Fast breeder reactor (FBR)
Advanced heavy water reactor (AHWR)

ABSTRACT

The paper gives a summary of the developments carried out for over four and a half decade in the field of nuclear fuel fabrication for power reactors in India. The facility at Nuclear Fuel Complex (NFC)is unique in the world with fully integrated manufacturing of fuel and core structural for the Pressurized Heavy Water Reactors (PHWRs), Boiling Water Reactor (BWR) and Fast Breeder Reactors (FBRs)operating in India. The integrated processing starts with the ore which is processed through several intermediate products to the finished fuel assemblies and several core structurals. The paper covers a summary of challenges encountered in technology development of materials and processes and their solutions arrived by carrying out detailed studies. The paper gives an overview of automation and advanced quality control methods used in the production line for capacity building to meet the enhanced fuel requirement. The paper also gives an outline of the future expansion program for fuel fabrication for enhancing the installed capacity of nuclear energy in India.

1. Introductionintroduction

India is following closed fuel cycle option with reprocessing and recycle of uranium and plutonium (U and Pu) for power generation. The main advantage of the closed fuel cycle lies in the efficient utilization of plutonium for power generation as it can increase the quantum of energy that can be derived from a given amount of uranium which varies depending on the reactor systems used. Thus closing the nuclear fuel cycle by reprocessing the spent fuel and recycle of U and Pu helps in achieving the goal of exploiting the full potential of nuclear power. The nuclear energy programme in India envisages three stages of implementation involving installation of uranium fueled thermal reactors in the first phase followed by utilization of plutonium in fast breeder and in the third phase, utilization of reactor systems based on U233– Th cycle, which we consider to be the ideal fuel cycle of the future, from Indian context. Nuclear Fuel Complex plays the most important role in fuel fabrication activity for the first stage involving natural uranium and low enriched uranium fuel as well as the hardware required for PHWR and BWR fuel cores while Uranium ore processing is done by UCIL. For the second stage the fertile/fissile materials required for the fast reactor core are depleted/reprocessed uranium and plutonium obtained by reprocessing of PHWR spent Fuel. The reprocessing and the plutonium bearing ((U-Pu) Mixed carbide or Mixed Oxide) fuel fabrication for the fast reactor is the responsibility of BARC but the fabrication of radial blanket and other core structural as well as assembling of Pu bearing fuel pins for the fast reactor core is the responsibility of NFC. AHWR is representative of third stage which can be fueled by (Th-LEU) or (Th–Pu) or (Th–U-233) fuels and NFC has the responsibility for manufacturing nuclear fuel for (Th-LEU) version of AHWR and the fuel for other latter versions of AHWR is to be made at BARC. Thus NFC plays an important role in the area of Nuclear Fuel Fabrication for all three stages of Indian Nuclear Power Programme. The scope of the paper is to briefly describe the developments and challenges in nuclear fuel fabrication activities at NFC.

Nuclear fuel cycle starts with mining of uranium ores from the earth and terminates with the disposal of nuclear waste/spent nuclear fuel in deep geological repositories. The complete set of processes involved in the conversion of uranium ore to uranium fuel for the nuclear reactors are known as front end of the nuclear fuel cycle whereas the operations/steps involved in the management and disposal of spent nuclear fuel/nuclear waste are known as back end operations. Activities in the front end in nuclear fuel cycle-mining, processing, quality control and performance evaluation are described in the following sections in detail.

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http://dx.doi.org/10.1016/j.pnucene.2017.03.005
0149-1970/

1.1. Mining and milling of ore

In India, uranium is mined from the mines of UCIL at Jaduguda and Tummalapalle(Gupta and Sarangi, 2011; Gupta et al., 2003; Suri, 2010). The nature of mining is governed by the nature of the ore body, geological conditions and economic considerations. The mined ore is first crushed, wet ground followed by extraction of uranium by hydro-metallurgical processes which involves chemical leaching, filtration, purification and precipitation. The nature of the leaching agent is dependent on the composition of the constituents of the ore.

In Jaduguda, the ground slurry is pumped into "pachuas" for leaching out uranium from the ore using sulphuric acid and MnO_2 as oxidant (Gupta et al., 2003). Uranium in the leached slurry is purified and concentrated by anionic ion-exchange method. This concentrated liquor is then reacted with dolomite (MgO) to precipitate uranium as magnesium diuranate or MDU (Fig. 1).

In Tummalapalle, the mined ore, after conventional crushing and grinding is thickened, repulped and subsequently subjected to alkali leaching by sodium carbonate and sodium bicarbonate solution in a series of leaching tanks/autoclaves (Suri, 2010). The leached filtrate after clarification and precoat filtration is subjected to precipitation with sodium hydroxide. The final product, at a pH of 12 or above will precipitate as sodium uranate (SU). Both MDU and SU are dried, packed and sent to NFC for further processing.

1.2. Nuclear fuel production

NFC produces both natural and enriched fuel assemblies for PHWR and BWR respectively. Natural uranium ore concentrates received in the form of UOC, MDU, SU, HTUP etc. while for enriched stream the input material is in the form of UF_6. Enriched uranium pellets of 1.6, 2.1 and 2.66% ^{235}U are used for manufacturing 6 × 6 BWR fuel assemblies for TAPS 1 and 2.

1.2.1. PHWR fuel production

The ore concentrates as received from the mills are usually processed through a series of chemical and metallurgical processes for conversion into nuclear grade UO_2. The ore concentrates are dissolved in nitric acid and converted to crude uranyl nitrate $UO_2(NO_3)_3$solution for further purification. This crude uranyl nitrate solution is then purified by solvent extraction with a mixture of 30% TBP as solvent diluted with Kerosene. Multi stage pumper decanter cascade of solvent extractors are used which can handle up to 20% solids in the input solution. In this process, Uranium is selectively extracted into the extract stream while the impurities remain in the raffinate stream. The uranium rich extract stream is stripped with DM water to produce pure uranyl nitrate solution. This pure uranyl nitrate solution is then precipitated with vapour ammonia for the production of ammonium diuranate (ADU) slurry (VenkataSwamy et al., 2015). SEM image of ADU powder is shown in Fig. 2. ADU slurry obtained after precipitation is filtered and dried. The dried powder is calcined in air at 600 °C. In this step, ADU powder decomposes into triuranium octaoxide (U_3O_8).

This U_3O_8 is then reduced in cracked ammonia atmosphere to obtain nuclear grade UO_2 powder. UO_2 powder this obtained is pyrophoric in nature and it oxidizes once in contact with air forming U_3O_8. Thus, UO_2 powder need to be stabilized under controlled oxidative atmosphere to form a thin layer of U_3O_8 on UO_2 kernel. This stabilized UO_2 powder is then sent to the pelletization section for pellet fabrication. Typical flow sheet for UO_2 powder production along with the stage wise QC steps are given in Fig. 3.

Qualified UO_2 powder lots are processed through powder-pellet route. The poor flowability of UO_2 powder due to fine particle size requires pre-compaction and granulation operations. The granulated powder is mixed with organic lubricant for reducing die-wall friction during final compaction operation. In final compaction, the powder is pressed into green pellets which are sintered in reducing atmosphere at high temperature to attain specified high density pellets with required O/U ratio (Ganguly, 2001). The O/U ratio and sintered density of the pellet have an effect on the thermal conductivity which controls the centre-line temperature and fission gas release. Pellet ends are designed with dishes to accommodate thermal volumetric expansion of the plastic core of the pellet. The pellet ends are chamfered on the edges of the flat pellet surfaces to minimize pellet chipping during loading and subsequent element handling. Chamfering also reduces sheath strain at pellet interfaces (Jobin Koshy et al.,). Typical flow sheet for UO_2 pellet fabrication along with the stage wise QC steps are given in Fig. 4.

The Zirconium alloy tubes are end machined to get the required profile and length. Zircaloy 4 appendages like spacer and bearing pads are welded on these tubes as per design requirement by resistance projection welding. The spacer and bearing pads used in the fuel assembly along with the stage wise QC steps are shown in Fig. 5.

Before pellet loading operation, the fuel clads are coated on the inner surface with a thin layer of graphite and are baked under high vacuum. This reduces pellet-clad interaction. The void within the fuel elements is filled with a He/air or He/inert gas mixture prior to endcap welding. The presence of helium in the fuel element allows leak detection during fabrication and provides some improvement in the pellet-to sheath heat transfer. Fuel element closure is provided by two end caps (Fig. 6) that are resistance welded to the ends of the clad (Satish Kumar et al., ; Setty et al., 2008). Typical flow sheet for PHWR fuel fabrication along with the stage wise QC steps are given in Fig. 7.

Several automated welding and assembly operations are carried out using state of art robotic machines. One such robotic end plate welding machine is shown in Fig. 8.

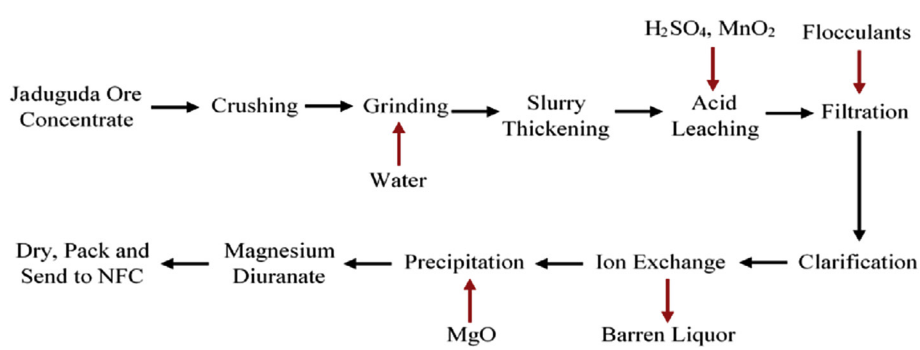

Fig. 1. Typical milling flowsheet of Jaduguda ore.

Please cite this article in press as: Setty, D.S., et al., Nuclear fuel cycle - developments and challenges in fuel fabrication technology in India, Progress in Nuclear Energy (2017), http://dx.doi.org/10.1016/j.pnucene.2017.03.005