Historical Development of Nuclear Fuels Fabrication and Related Facilities in BARC

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Preamble

This article traces historical development of nuclear fuel fabrication and development of related facilities in Bhabha Atomic Research Centre (BARC). This is written keeping in view science students or persons from different walks of life but not related to development of nuclear energy. The article will cover general aspects of nuclear fuel, fissile materials, historical background of nuclear fuel fabrication in India and salient details of some of the types of nuclear fuel fabricated by BARC. It will also highlight efforts made in development of non-destructive examination of fuel, post irradiation examination facilities and future thrust areas in nuclear fuel fabrication.

1. Introduction

Thermal energy in a nuclear reactor is liberated from fission reactions. These reactions take place inside the nuclear fuel therefore, fuel acts as the primary source of energy and hence it is the key requirement of nuclear reactors. Nuclear fission was discovered and understood by combined efforts of several scientists; chief among them were Enrico Fermi, Otto Hahn, Lise Meitner, Fritz Strassmann, Otto Frisch, Leo Szilard, Niels Bohr, during the years 1934 to 1938. Initially studies were focused on fission of heavy nuclei like uranium. In a fission reaction, heavy nuclei splits into two nuclei, called fission fragments. Most of these fragments are radioactive and further their combined mass is slightly less than the original mass of heavy nuclei. This missing mass is of the order of 0.1 % of the original mass and it is this mass which is converted into energy, of an amount given by Einstein's energy-mass equation: $E = mc^2$. The energy per fission reaction is about 200 MeV (= 32.18×10^{-12} J). The resulting energy density, inside the nuclear fuel, is three million times compared to about 60 eV per reaction from combustion of fossil fuels, like coal. In addition, the fission reaction also yields 2 or 3 neutrons along with gamma photons. A typical fission reaction is shown schematically in Fig. 1(a). It was soon realized that these neutrons can be utilized to sustain stable fission chain reactions and continuous energy generation is feasible, see schematic in Fig. 1(b). This realization immediately led to an intense development of ways and means to harness this energy and the activities progressed with rapidity unprecedented in the history of scientific and technical research.

The result was creation of "Chicago Pile", at University of Chicago, in December, 1942. This was the World's first nuclear reactor; employing fission reactions as source of energy. Its fuel comprised of metallic natural uranium as well as natural uranium dioxide (UO_2). Metallic uranium of desired purity could not be processed in those days hence UO_2 was also used. Metallic uranium was in the form of slugs while UO_2 was compressed into circular disks (called "Briquettes" at that time), employing best techniques of powder metallurgy known at that time. In those days understanding of uranium metallurgy, to fabricate nuclear fuel, was a great challenge.

The natural uranium, employed as fuel constituent in "Chicago Pile", comprises of mainly 0.7% uranaium-235 isotope (U-235) and rest is mainly uranium-238 (U-238). Out of this main source of fission is U-235 and is one of the three known "Fissile Materials". U-238 also undergoes fission but with only high energy neutrons however, the contribution is very small and such materials are called "Fissionable Material".

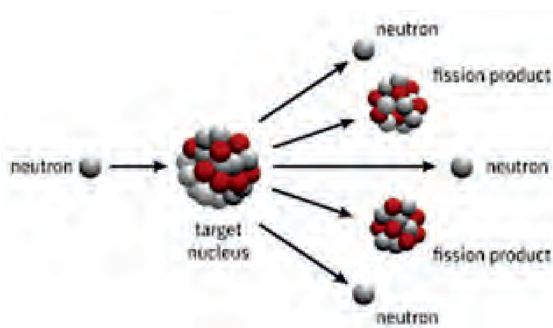

Fig. 1(a): Schematic of fission reaction inside any nuclear fuel. Each reaction yields 200 MeV and 2 or 3 neutrons. The energy density is very high. 1gm of U-235 yields 82000 MJ of thermal energy, which is equivalent to combustion of about 3000 tons of coal. Therefore, nuclear fuel design and fabrication is a challenge

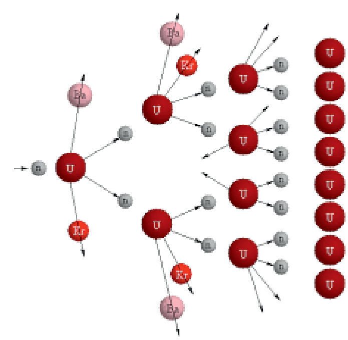

Fig. 1(b): Schematic of sustained and stable fission chain reaction. It is possible with incorporation of suitable absorber materials, which in turn ensure only one neutron enters into fission of next generation

Fission became a new source of energy after combustion of coal or oil or gas. Following successful project of "Chicago Pile", scientists and engineers immediately initiated activities towards utilization of nuclear fission for generation of large scale electricity and naval propulsion. In May, 1954 Obninsk Nuclear Power Plant, Russia, (then known as Soviet Union) became first Nuclear Power Plant (NPP) to be connected to electrical grid and produced 5 MW of electrical power. The nuclear fuel was 5% enriched uranium, that is, the concentration of U-235 isotope was kept equal to 5%, as against 0.7% in natural uranium. Such isotopic enrichments are achieved by physical or mechanical separation techniques.

In January, 1955, United States Navy succeeded in operationalizing compact nuclear reactor for propulsion of submarine called "USS Nautilus", which became world's first nuclear submarine. It utilized zirconium cladded "Plate Type" fuel with Highly Enriched Uranium (HEU), having U-235 isotopic concentration of about 93%. HEU was essential for maintaining compact size and facilitating long refueling periods.

On August, 4, 1956, first Indian nuclear reactor, called APSARA, became critical. This was not only first in India but was also the first reactor in whole of Asia. It was designed by scientists and engineers of Bhabha Atomic Research Centre (then known as Atomic Energy Establishment, Trombay). It utilized plate type fuel having Uranium Aluminide alloy with Aluminum Clad. APSARA fuel also utilized HEU having U-235 isotopic concentration of about 93%.

Starting 1960s, worldwide large scale efforts were put towards technological development of robust and safe nuclear reactors for generation of electric power, naval propulsion, advanced nuclear research and medical/industrial isotope production. Nuclear energy is attractive because of three main reasons listed below. Nuclear fuel design and fabrication plays important role in all of these advantages.

(a) It is a source of green energy and almost no pollution, as compared to fossil fuel based plants, see Fig 2(a) and Fig. 3(a). Nuclear has very low carbon foot print. A typical 500 MWe coal combustion plants release CO_2 at rate of about 10000 ton per day and in contrast such releases from nuclear plant are insignificant. The fission fragments, including radioactive gases are retained within the nuclear fuel.

(b) Owing to high energy density, the fuel loading in nuclear reactors is infrequent and hence its demand on transportation infrastructure is insignificant as compared to coal or oil based thermal plants. For comparison, see Fig. 2(b) and Fig. 3(b). This fact is among the important factors responsible for relatively low operational cost of nuclear reactors.

(c) Nuclear energy also standouts among several types of renewable sources of energy, owing to its continuous or base load operation capability. This in turn is related to infrequent loading requirements of nuclear fuel. For example, annual electricity units generated by nuclear plant is roughly 3.3 times more than the solar energy station of same installed electrical capacity. This factor varies with the climate. It is higher during cloudy or rainy or snowing or dusty periods. It also increases as we move from equator towards poles. Capacity Factor (CF) of nuclear plants is generally high, for example, Unit # 1 of Kaiga Generating Station, in India, operated at full power continuously for 895 days.

As of the year 2021, there are about 450 numbers of nuclear power reactors all over the world producing about 400 GW of electrical power. In India, there are 22 nuclear power reactors with installed capacity of 6.75 GW of electrical power. Worldwide, 50 numbers of power reactors are under construction and among them 8 are in India. Worldwide 100 more power reactors are planned in immediate future and among them major percentage is in Asia.

The rest of the article will cover general aspects of fuel, fissile materials, overview of development of fuel fabrication and related facilities at BARC. The fabrication technology of fuel for Indian power and research reactors was fully developed by BARC. Currently the fabrication is being carried out by BARC and Nuclear Fuel Complex (NFC), Hyderabad.

2. General Aspects of Nuclear Fuel and Types of Fissile Materials

The nuclear fuel mainly comprises of nuclear material, clad, and structural material. It is the fissile content of nuclear material, which undergoes bulk of the fission reactions. The clad covers the nuclear material and its material selection and design ensures that the fission fragments are not released out under any normal operating condition and any design basis accident condition. Structural materials are required for formation of fuel assembly or fuel bundle and to locate the fuel assembly/bundle inside the reactor such that it maintains desired pitch/inter-space distance as demanded by reactor physics considerations and remains coolable under all the operating, design basis accident conditions and to the extent possible even during beyond design basis accidents. The coolant carries the heat from the fuel for further conversion to useful forms.

Fig. 2(a): A typical coal fired thermal power station. A typical 500 MWe coal fired unit releases about 10000 tonnes per day of CO_2, which has major bearing on green-house effect. In addition, copious amount of So_2, NOX gases and harmful Particulate Matter (PM) amongst others are also released. In the year 2021 India emitted about 1.4 billion tonnes of CO_2 owing to coal firing at power stations alone

Fig. 2(b): Transportation of coal from mines to power station site is expensive and puts heavy demand on transportation infrastructure. A typical 500 MWe unit demands two 50 wagons goods train carrying 5000 tonnes of coal daily from mines to power station site. In the year 2021 about 700 million tonnes of coal was transported for different utility and captive power stations in India

Fig. 3(a): 540 MWe Tarapur PHWRs Unit # 3 and 4. Nuclear plants do not release any pollutants and its carbon foot print is negligible. Nuclear fuel design and high quality fabrication assures that fission fragments and gases are retained within the fuel and hence there are no releases outside the reactor system

Fig. 3(b): Nuclear fuel is transported in trucks. 4 to 5 truck trips meet the annual nuclear fuel requirements of a typical 540 MWe Unit

There are three known nuclear fissile isotopes- Uranium-235 (U-235), Plutonium-239 (Pu-239) and Uranium-233 (U-233). Amongst them, only U-235 exists in nature. Natural uranium comprises mainly of 0.7% U-235 and about 98.3% U-238. The concentration of U-235 was about 32% during early stages of formation of earth. Owing to radioactive decay the isotopic concentration reduced to about 3% about 2 billion years back and now it is 0.7%.

Pu-239 existed after formation of universe but got exhausted by natural radioactive decay, before the earth was formed. About 2 billion years ago when the concentration of U-235 was about 3%, in natural uranium, an anomaly occurred at Oklo, Gabon, located in West Central Africa. Under the natural conditions prevailing that time a self-sustaining natural fission chain reaction initiated in which more than 500 tonnes of U235 fissioned leading to generation of Pu-239. This was the second occasion in which plutonium was formed in nature. However, over a period of 2 billion years this has decayed fully (having half-life of 24×10^3 years) leaving the trace of uranium unusually depleted in U-235 concentration thereby giving the secret away. Now Pu-239 does not exist in nature. However, Pu-239 is artificially transmuted from U-238, in nuclear reactors by neutron irradiation. In this manner, U-238 participates in fission reaction indirectly. Such isotopes which get transmuted to fissile isotopes are called “Fertile Materials”. Therefore, U-238 is both “Fissionable” and “Fertile”.

U-233 also does not exist in nature however; there are vast reserves of Thorium-232 (Th-232) in several parts of world. Th-232 can be artificially transmuted to U-233 by neutron irradiation in nuclear reactors hence this is also a fertile material.

In India, the relative abundance of thorium is far more as compared to known reserves of uranium. World's largest reserves of thorium are available in the beach sands of Kerala. Typical view of Kerala beach sands is shown in Fig. 4. Transmutation of Th-232 to U-233 requires large quantity of fissile materials. In order to maximize utilization of thorium, the Indian policy planners chalked out “Three-Stage Nuclear Power Programme” and hence adopted closed fuel cycle. The first stage programme involves construction and operation of uranium fueled reactors. In these reactors, while power is generated but another important output is transmutation of fertile U-238 to plutonium. Major thrust is on Pressurized Heavy Water Reactors (PHWRs), which produce highest quantity of plutonium per unit quantity of mined natural uranium. PHWRs are now fully indigenized. In addition, spent-fuel recycling facilities were also designed, constructed and now are being operated. The PHWR spent-fuel is being recycled to separate plutonium and depleted uranium. As plutonium is produced, various technologies were considered for boosting the quantity of plutonium further. The plutonium along with depleted uranium would fuel the reactors in the second stage, that is, in Fast Breeder Reactors (FBRs). The effective utilization of plutonium and transmutation of U-238 to Pu-239 is high under fast energy neutrons. The fuel for Prototype Fast Breeder Reactor (PFBR), which is under construction, is uranium-plutonium mixed oxide and is being fabricated based on powder metallurgy route. In the second stage the U-238 to plutonium breeding efficiency will be significantly high if “Metallic Plutonium-Uranium” nuclear fuels are used. Considerable efforts are underway to develop suitable uranium-plutonium metallic fuel for future FBRs. It is important to note that for optimal balance between utilization, fuel fabrication aspects and meeting adequate reactor safety margins, it is required that plutonium concentration in plutonium-uranium mixed oxide fuels is limited to about 30%. In case of metallic fuel, it should not exceed 15% to 20% to ensure absence of undesirable metallurgical phases. Exceeding plutonium beyond this limit will induce brittle phases, which in turn will deteriorate the fuel performance.

Fig.4: A typical view of Kerala beach coastline containing rich Thorium reserves. As of year 2020 the estimated thorium reserves, in India, stand at about one million tonnes. The concentration of Thorium is reasonably high and the typical radiation field in these beach sands is around 1 mR/h. At some of the locations peak radiation field is 2 mR/h. These beaches are well inhabited and in addition fairly large numbers of tourists visit regularly. [Note: In contrast the radiation field around any nuclear power plant of India is 100 to 200 times less than the average radiation field of Kerala beach sands. Despite this exclusion zone of minimum one km is maintained around the nuclear power plants and additional 5 km of sterilized zone exists]

Once sufficient plutonium is available and power production is reached wherein self-sufficiency is achieved, further growth in nuclear energy has to be achieved through breeding of U-233 from thorium within the fast breeder reactors. The third stage of Indian nuclear power progarmme would consist of utilizing U-233 for power production as well as breeding Th-232. The prospective reactor concepts are under formative stages. Some of these include fast breeder reactor, molten salt breeder reactor etc. In addition, Advanced Heavy Water Reactor (AHWR) is also being developed for technology demonstration towards thorium utilization and innovative passive safety systems. This is the “Key” to self-reliance in nuclear power even with limited uranium resources.

3. Historical Background of Fuel Fabrication in India

For APSARA research reactor (see Fig. 5(a)) the nuclear fuel was imported from The United Kingdom (UK). Thereafter, BARC carried out massive research and development in nuclear fuel fabrication. This resulted in several fuel fabrication facilities and in-house fuel for all the subsequent research and power reactors built in India. APSARA reactor pool and core are shown in Fig. 6(a) and Fig. 6(b).

Shortly after successful commissioning APSARA, the Canada India Reactor Utility Services (CIRUS) reactor (see Fig. 5(b)) construction started in active collaboration with Canada and first criticality was achieved in July, 1960. In order to fabricate fuel for CIRUS reactor two important facilities namely Uranium Metal Plant (UMP) and Fuel Element Fabrication Facility (which later was called Atomic Fuels Division (AFD)) were created at BARC. Expert Indian metallurgists worked on these projects, which resulted in understanding uranium metallurgy and development of fuel for CIRUS. This was the first ever nuclear fuel made in India and first consignment was delivered in 1959 (see Fig. 7(a)). At that time, this was one of the towering achievements of BARC. Shortly later Zero Energy Reactor for Lattice Investigations (ZERLINA) reactor fuel (in 1961) was developed on the lines of CIRUS reactor fuel.

In the years after CIRUS operationalization, research and development activities were initiated towards for new fuel fabrication techniques for metallic fuels, ceramic fuels and dispersion fuels. Technologies related to Powder Metallurgy (PM) and Ingot Metallurgy (IM) based routes were successfully developed, for fuel fabrication. These initiatives came handy when nuclear programme expanded further.

Fig. 5(a): APSARA Reactor: Outer View of Reactor Building. Fuel and Pool Details shown in Fig.6(a) and Fig. 6(b). (Operations started in the year 1956)

Fig. 5(b): CIRUS Reactor: Outer View of Reactor Building. Fuel details are shown in Fig. 9. (Operations started in 1961)

Fig. 6(a): APSARA, the pool type reactor is Asia first reactor which began operations in 1956. The figure above shows perspective view of APSARA reactor along with pool and top bridge houses structures for control rod drives. (see external view in Fig. 5(a))

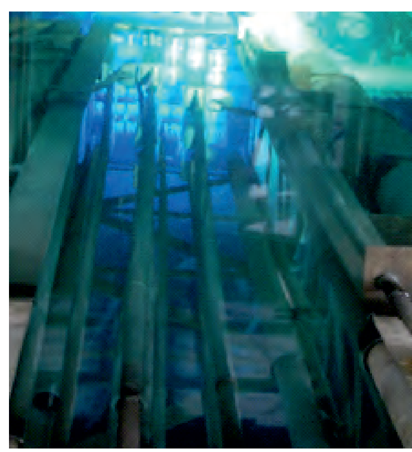

Fig. 6(b): APSARA Reactor Core while in operation, as seen from top of the pool. The view shows blue glow owing to Cherenkov Radiation from water within and around Fuel Assemblies (Plate Type)

Apart from fuel fabrication technologies, impressive developments were made in the area of Non-Destructive Examination (NDE) for assuring desired quality of fuels. The qualification of CIRUS fuel, for reactor, called for sound quality and tight quality control. In the year 1960 Ultrasonic Testing (UT) was used on cast uranium billet to detect piping and shrinkage cavity type of defects. Later Eddy Current Testing (ECT) was introduced for uranium fuel rods for detection of pitting, tool marks and slag inclusions on the surface, which are sites of potential hydride blister formation. During that time NDE methods like UT or ECT were unheard in Indian industry. In fact, application of UT to examine fuel was one of earliest application of this NDE technique in India. Application of UT and ECT for examination of uranium billet and rod are shown in Fig. 7(b).

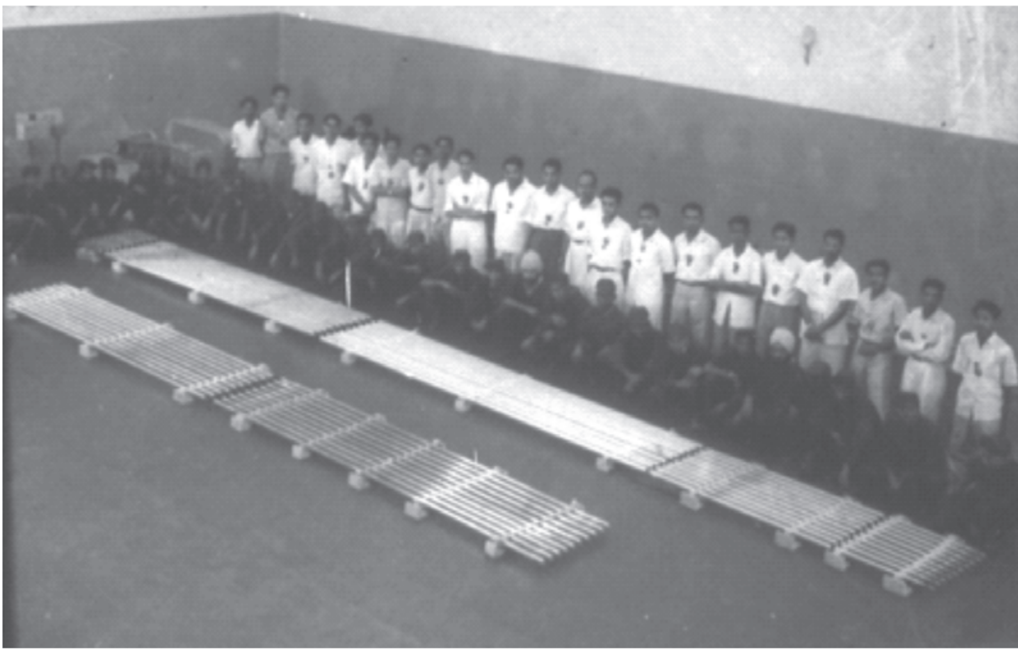

Fig. 7 (a): First consignment of fuel rods was delivered to CIRUS in 1959. The fuel is natural uranium metallic fuel. Metallic uranium fuels, till date, are fabricated only at BARC-Trombay. CIRUS reactor achieved criticality in July, 1960. (Much later, in the year 1984 production of metallic uranium fuel for Dhruva reactor was initiated at facilities created for CIRUS reactor)

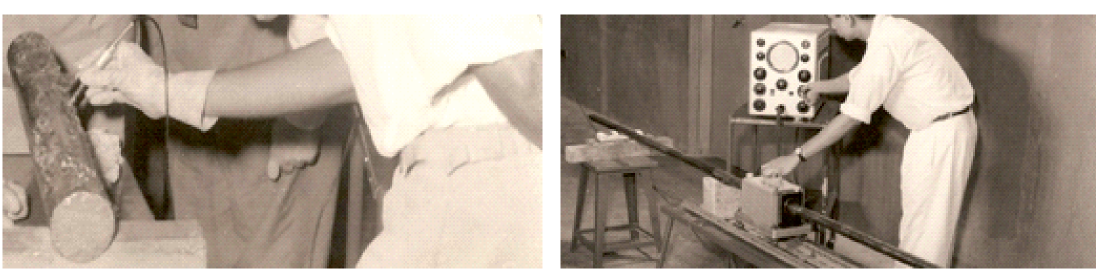

Fig. 7(b): Left Picture -Ultrasonic Testing (UT) of uranium billet for CIRUS Fuel. Right Picture-Eddy Current testing (ECT) of CIRUS rod. These techniques were developed at a time when there was no know how of this subject, in Indian industry. Later experts from BARC took active initiative in disseminating knowledge gained in this field, to specialists of other industries.

Beginning of 1960's, India took bold step towards indigenous creation of Nuclear Power Plants (NPPs). To be consistent with our policy of Three Stage Programme, it was decided to build CANDU type of nuclear reactors. This activity was initiated in collaboration with Canada. After first two units at Rajasthan Atomic Power Station (RAPS-1 & 2), Kota, the technology was fully indigenized and several modifications were successfully incorporated in later units, built in India. Subsequently these reactors were called Pressurized Heavy Water Reactors (PHWRs). The development of fuel for power reactors also began at BARC and the natural uranium dioxide (UO_2) fuel bundles, for first core, was successfully fabricated and delivered during the years 1970 to 1971; see Fig. 8. RAPS-1 achieved first criticality in 1973. Later PHWR fuel fabrication technology was transferred to Nuclear Fuel Complex (NFC), which at that time was newly created for fabrication of power reactor fuels. As of now natural uranium oxide fuel bundles, for all PHWRs, are fabricated at NFC, Hyderabad. A new centre of NFC is under construction at Kota. This will facilitate fuel fabrication for new 700 MWe PHWRs. Over the years several improvements have been incorporated in the PHWR fuel fabrication facilities at NFC.

Fig. 8: First batch of Power Reactor Fuel for RAPS-1 PHWR was made in BARC and delivered during the period 1970 to 1971. Powder Metallurgy (PM) based technologies were established to fabricate fuel using natural uranium-dioxide. RAPS-1 achieved criticality in the year 1973. PHWR fuels are now fabricated at Nuclear Fuel Complex (NFC)-Hyderabad

In the year 1965 fuel reprocessing plant called Plutonium Plant (PP) was successfully commissioned at BARC. In 1968 plutonium production was started which marked the beginning of era of plutonium metallurgy in India. Plutonium is highly radio-toxic material and its handling requires extensive safety measures. In order to develop plutonium based fuels and understand the radiochemistry aspects, special radiological laboratory was commissioned in 1968, at BARC, Trombay. Active research by several expert radio-metallurgists resulted in development of plutonium fuels for research and power reactors.

Plutonium based fuel was first time fabricated for Plutonium Reactor for Neutronic Investigations in Multiplying Assemblies-I (PURNIMA-I), in May, 1972. Later technologies were developed for fabrication of fuel for Fast Breeder Test Reactor (FBTR) in October, 1985.

The FBTR fuel is uranium-plutonium mixed carbide. Radiological laboratory houses the only plant in the world for fabrication of mixed carbide fuel. This also marked the beginning of movement towards closed fuel cycle. Till date very few countries have mastered technology of plutonium based fuels.

Another important achievement was successful development of fabrication technology of uranium-plutonium (U-Pu) mixed oxide fuel for TAPS-BWRs (Tarapur Atomic Power Station Boiling Water Reactors Unit 1 & 2). This reactor was constructed and erected by General Electric Company, USA. Its fuel is Slightly Enriched Uranium (SEU) oxide based and is fabricated at NFC, Hyderabad. SEU import is under international safeguards. In the years following India's Peaceful Nuclear Explosion (PNE) in 1974, there was disruption in SEU supply. With the aim of reducing dependence on import of SEU indigenous development was carried out to fabricate U-Pu mixed oxide fuel for TAPS-BWR-1&2. Initial development was carried out at radiological laboratory, BARC, Trombay.

Successful operation of the radiological facilities at BARC, Trombay, led to creation of a larger facility at BARC, Tarapur, for fabrication of uranium-plutonium mixed oxide (MOX) fuels for fast breeder power reactors. This is known as Advanced Fuel Fabrication Facility (AFFF). Plutonium was first introduced, in AFFF, in the year 1993. Based on the technology developed at radiological laboratory, BARC, several fuel assemblies of U-Pu mixed oxide fuels were fabricated for TAPS-BWR-1&2. This was followed by fabrication of MOX fuel for fast breeder reactors.

In the year 1984 PURNIMA-II attained criticality and it was first reactor in India to operate using U-233 based Uranyl Nitrate solution. The core was basically homogenous solution of U-233. Subsequently in the year 1990 PURNIMA-III became critical using U-233 as fissile material. The fuel was plate type with aluminum clad. U-233 was transmuted by irradiating thoria in CIRUS reactor. Thoria was in the form of sintered pellets stacked in aluminum rods. These rods were fabricated in facilities were CIRUS fuel was fabricated. The U-233 fuel was fabricated in radiological laboratories of BARC. PURNIMA-III and its fuel was precursor to Kalpakkam Mini (KAMINI) reactor located at IGCAR, which achieved criticality in October, 1996. KAMINI reactor is the only reactor in the world using U-233 as driver fuel.

As part of civil nuclear cooperation agreement with USA, India decided to permanently shut-down the APSARA reactor in the year 2009. Thereafter, new swimming pool type reactor APSARA-U (See Fig. 13) was designed and constructed at BARC. Its fuel is Light Enriched Uranium (LEU) silicide cladded in aluminum plates. This was developed indigenously and has been fabricated successfully at radiological laboratory, BARC, Trombay.

In case of imported reactors, the TAPS-BWR-1&2 fuel is fabricated at NFC while that of Russian VVERs at Kudankulam the fuel is imported from Russia itself. Feasibility of fabrication within India is being actively explored.

The remaining part of the article covers the brief description of fuels fabricated for some of the research and power reactors, the development of fuel NDE techniques, post irradiation examination of discharged fuel and research and development areas for future fuels.

4. Brief Description of Nuclear Fuels Fabricated by BARC

4.1 Fuel for CIRUS Reactor

Uranium Metal Plant (UMP) and Fuel Element Fabrication Facility (FEFF) were set up for production of nuclear grade uranium metal ingots and metallic uranium fuel rods for CIRUS reactor, see Fig. 9. The first uranium ingot was delivered by UMP in January, 1959 and a prototype fuel element was fabricated in June, 1959. Fuel for CIRUS reactor was in the form of a natural uranium metal rod cladded in aluminium, see Fig. 9. Like APSARA reactor, CIRUS reactor was also permanently shut-down, in the year 2010, following civil nuclear cooperation agreement with USA.

4.2 Fuel for ZERLINA Reactor

Fuel for the ZERLINA reactor was developed on same lines as that for CIRUS reactor. The ZERLINA and CIRUS fuel differ mainly in geometrical sizes.

Fig. 9: Natural uranium metallic fuel fabrication facilities for CIRUS and Dhruva Reactor. Clockwise from top left: (a) Uranium metal ingot undergoing cutting. (b) Vacuum melting and casting facilities for uranium billets. (c) Fuel machining facilities. (d) Fuel rods for CIRUS Reactor

4.3 Fuel for Dhruva Reactor

Dhruva fuel, like CIRUS fuel, is also essentially metallic natural uranium with aluminium clads. However, unlike CIRUS Fuel, this fuel assembly comprises of cluster of 7 pins arranged in aluminium tubes by tie plates and spacers. The photograph of DHRUVA fuel sub-assembly is shown in Fig. 10.

Fig. 10: Dhruva Reactor Fuel Clusters. Left figure shows the overall assembly (3 numbers of them are seen). Right figure shows end view of one of the assemblies. It is a cluster of 7 fuel pins. Dhruva fuel fabrication facilities are more or less identical to those of CIRUS fuel, shown in Fig.9

4.4 Fuel for PURNIMA-I Reactor

One of the first outcomes of expertise developed in plutonium metallurgy was fuel fabrication for PURNIMA-I reactor. PURNIMA-I was a fast reactor. The fuel elements consist of a stack of sintered PuO_2 pellets, with an average density on 90% of theoretical. This gave invaluable experience of plutonium fuel performance and gave opportunity to reactor physicists to benchmark their computer programmes.

4.5 Fuel for FBTR

After PURNIMA-I, the major fast reactor to be designed and built was FBTR, which was operationalized in the year 1985. Its thermal power is 40 MWth. Its fuel is uranium-plutonium mixed carbide. Apart from radio-toxicity associated with plutonium, the carbide form is highly pyrophoric. The fuel is fabricated in ultra-high purity inert gas environment. Unlike in uranium-plutonium MOX or metallic forms the percentage of plutonium in mixed carbide form can be significantly higher than 30% (see section 2.0). In fact, in FBTR the PuC percentage is 70% hence it was possible to build compact core of FBTR. In case of uranium-plutonium MOX fuel, with plutonium fissile content restricted to 30%, and hence such compact core will demand significant quantities of enriched uranium. Carbide form with higher concentration of Pu-239 fissile material was opted for two reasons; firstly, unavailability of enriched uranium, in those days, and secondly the aim of adopting fast breeder technology was to enhance production of plutonium from limited resources of uranium. However, carbide form is very challanging to fabricate and requires several safety precautions. FBTR is the only reactor in the world using uranium-plutonium carbide fuel. FBTR fuel pellets and fabrication facilities are shown in Fig. 11. The fuel performance has been excellent and average burn-up is about 140 GW-Days/Tonne and peak burn-up of 165 GW-Days/Tonne.

4.6 Fuel for PFBR

PFBR is under construction, at Kalpakkam, and will be India's first fast breeder power reactor. It fuel is uranium-plutonium MOX, with plutonium oxide concentration less than 30%. The fuel is fabricated at AFFF, BARC, Tarapur and typical assemblies are shown in Fig. 12.

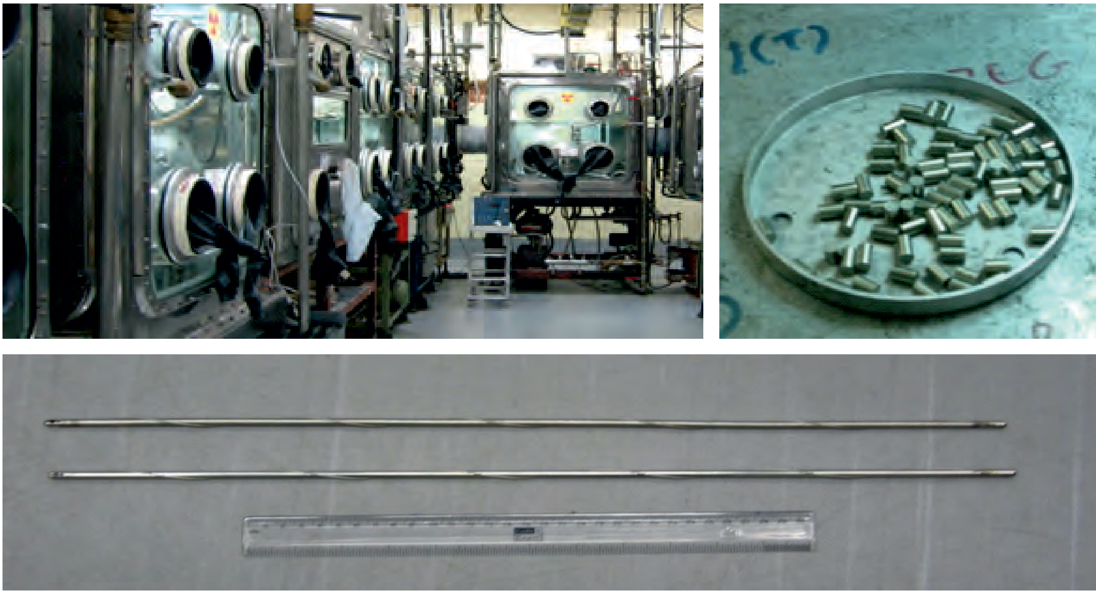

Fig. 11: Above: Glove Box Train for Uranium-Plutonium Carbide Fuel Pellet fabrication and fuel pellets inside the Glove Box. Below: Fuel Pin. The pellets undergo exhaustive physical and chemical quality control before they are accepted for fuel pin fabrication. Fabrication requires strict safety and operational measures. Glove boxes are leak tight to highest degree and operate under ultra-high purity inert gas atmosphere. Plutonium is highly radio-toxic and its carbide form is highly pyrophoric. Allowable plutonium concentration in air is 2.0 nano-grams/m^3 and inhalation of 20 mg is considered as LD50/60 lethal dose (that is, 50% of exposed persons will die in 60 days). The specially designed radiological laboratories account for strict requirements and include all the safety measures.

Fig. 12: Fuel assemblies for PFBR. It comprises of several pins each having uranium-plutonium MOX pellets. Since MOX is stable form of uranium and plutonium hence the fuel fabrication is carried directly in air media. However, leak tightness requirements are same as those of carbide fuel for FBTR (see Fig. 11) since radiological safety requirements are same for both. The fabrication is carried out at AFFF, BARC, Tarapur.

4.7 Fuel for APSARA-U Reactor

APSARA-U is upgraded version of old pool type research reactor APSARA. It has several new features as compared to earlier reactor. As brought out earlier; the APSARA fuel was HEU (~ 93% U-235) aluminide cladded in aluminium plates and was imported from UK. However, APSARA-U fuel was fully developed and fabricated by BARC. While developing the fuel, international practice of converting the reactor core from HEU to LEU was adopted. This was recommended by RERTR (Reduced Enrichment for Research and Test Reactor) programme which was later converted into GTRI (Global Threat Reduction Initiative) programme. Moving in line of international practices LEU-Silicide fuel was developed. Silicide facilitates higher loading of uranium hence the impact of reduction in enrichment is partly neutralized. The fuel has been successfully fabricated and has been put to operation in APSARA-U reactor. Fig. 13 shows the view of APSARA-U pool type reactor along with cutaway view of fuel assembly.

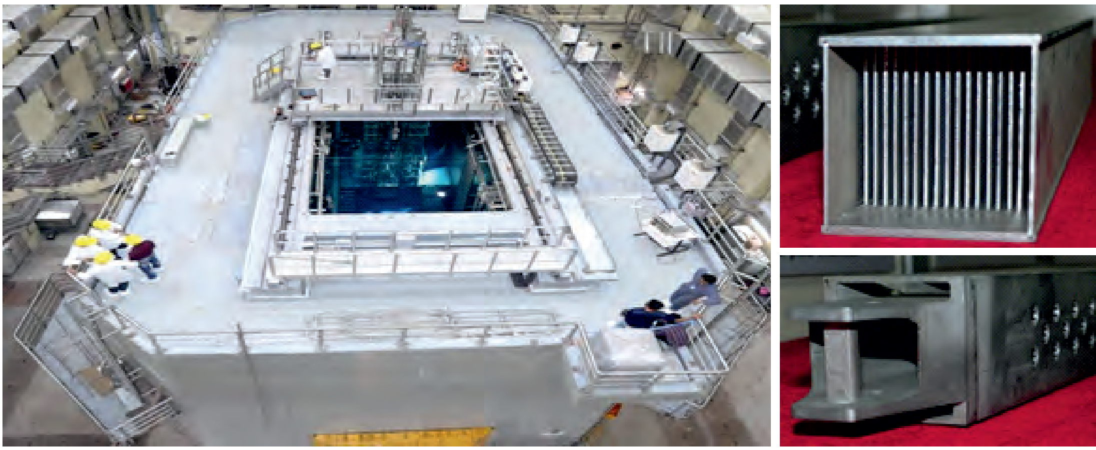

Fig. 13: Left Picture- APSARA-U reactor pool in operation. Bluish glow owing to Cherenkov radiation is seen. Right Pictures- APSARA-U fuel assembly Cut-away View and Full View. Uranium silicide fuel, for ASARA-U, is first of a kind in India

4.8 Fuel for KAMINI Reactor

The fuel for KAMINI reactor comprises of U-233 and pure aluminium mixture sandwiched in aluminium alloy clad. It is a plate type fuel and each assembly comprises of nine plates. Top view of KAMINI reactor along with its plate type fuel assembly is shown in Fig. 14. This fuel was first tested in PURNIMA-III reactor, at BARC, Trombay.

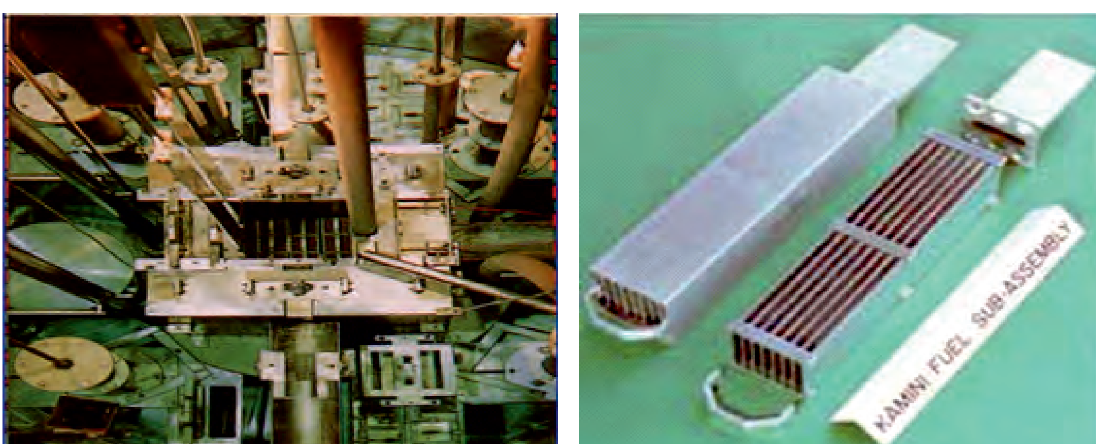

Fig. 14: Left Picture- Top View of KAMINI reactor. Right Picture- Plate type fuel assembly details. U-233 was handled with extreme safety precautions during plate fabrication at radiological laboratory, BARC. While irradiating Th-232, small amount of U-232 is invariably generated along with U-233. The concentration of U-232 increases with burn-up. The decay chain of U-232 produce hard gamma photons (energy = 2.6MeV) which poses radiological safety challenges in fabrication of fuels using such materials

5. Quality Control, Assurance and Development of NDE Techniques for Fuel

Quality assurance plays a vital role in performance of nuclear fuel that is manufactured indigenously for both research and power reactors. Variety of non-destructive examination (NDE) methods are employed during manufacturing of these fuels, which not only ensures that the design specifications are met, but also a close control on the manufacturing processes leading to lesser rejection and high recovery during production. Stringent quality assurance requirements during nuclear fuel fabrication has been responsible for *'first-time-use'* of variety of NDE methods in the country, such as ultrasonic and eddy current testing (see Fig.7(b)). Subsequently, these methods found applications in other core and industrial sectors. Even today, the demands during quality assurance of nuclear fuel is driving the growth in NDE science and technology leading to development of innovative and advanced NDE techniques.

Quality control during fabrication of fuel involves application of several destructive and non-destructive examination methods. Over the years several advancements have been implemented towards NDE of fuel during fabrication at BARC. As an example let us consider the case of Dhruva reactor fuel. Today every fuel clad tube and fuel element are eddy current tested using automated set-up. One of the critical weld joints is at junction between the plug and fuel clad. The geometry of these weld joints and stringent acceptance standards makes the task of inspecting each and every weld joint very challenging. X-ray radiography procedure has been developed for this purpose and is in use for the last several decades. Other tests that are employed during quality control of fuel include: glycol leak test of fuel elements, pneumatic and hydro-test for clad and flow tubes, mechanical testing for uranium rod, clad tubes and flow tubes, and visual examination at each and every step during assembly of fuel pins to form a cluster. Several innovative NDE techniques have been developed in the past few years to strengthen the quality assurance during Dhruva reactor fuel fabrication. One of the prominent amongst them is ultrasonic based critically refracted longitudinal wave technique for qualification of β-heat treatment of uranium rods. Post-extrusion, uranium rod develops texture, which needs to be randomized for assuring dimensional stability of fuel element during irradiation. Earlier practice to assure texture randomization was to subject small coupons to thermal cycling tests. These tests used to take several days and were possible on limited number of small coupons. Moreover, the test was destructive and hence could not be applied on every rod. The ultrasonic technique based on sound velocity measurement, is found to be very fast and accurate, and being non-destructive, is applied on all the rods, leading to comprehensive quality assurance and satisfactory performance of fuel cluster in the reactor.

Similarly, several advancements have been implemented in the production lines of power reactor fuel at NFC and BARC-Tarapur.

6. Post Irradiation Examination on Spent Fuels

BARC has created post irradiation examination (PIE) facilities for examination of spent fuels to evaluate fuel performance, understand reasons of premature failures and life limiting mechanism. Extensive studies are carried out at these PIE facilities (see Fig. 15 and Fig. 16) on different fuels. Some of these are for PHWR, Dhruva and APSARA-U reactor fuels. After the studies feedback goes to fuel fabricator for improvement in fabrication process. In addition PIE labs also have facilities for evaluating nuclear fuel clad integrity under accident conditions. More than 200 experiments have been conducted to quantify integrity of clads under accident conditions. Experiments are in progress and outcome of some of such experiments is shown in Fig. 17.

Fig. 15: PIE Hot Cell at BARC, for Metallurgical and Mechanical Studies on Irradiated Fuel and Reactor Core Materials such as Pressure Tubes of PHWRs. This is the Second Largest PIE Hot Cell in the world. It has 1.5 m thick concrete shielding and special Radiation Shielding Windows. Components having contact dose rate up to about 30000 R/h have been successfully handled in these hot cells

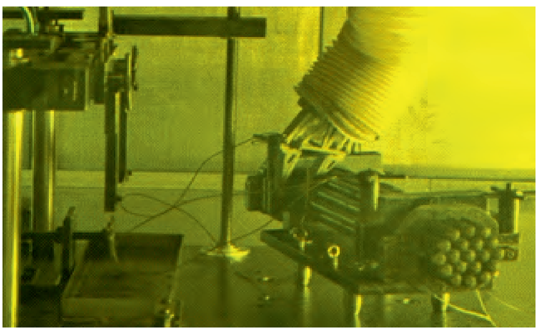

Fig. 16(a): Irradiated PHWR fuel bundle inside hot cell. The irradiated fuel bundles are received after different burn-ups for metallurgical examination (see Fig. 16(b)). Clad and structural materials are subjected to mechanical testing for determining ductility, burst strength etc.

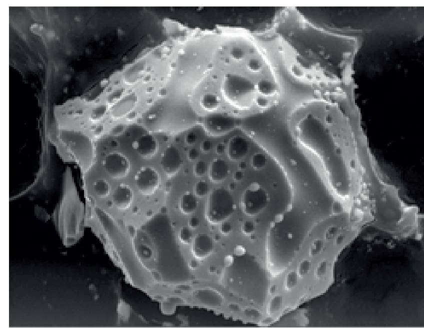

Fig. 16 (b): Grain from a high burn-up PHWR fuel showing fission gas bubbles, channels and metallic fission products. This is as seen in radiation shielded Scanning Electron Microscope (SEM). Grain size is ~ 30 μm

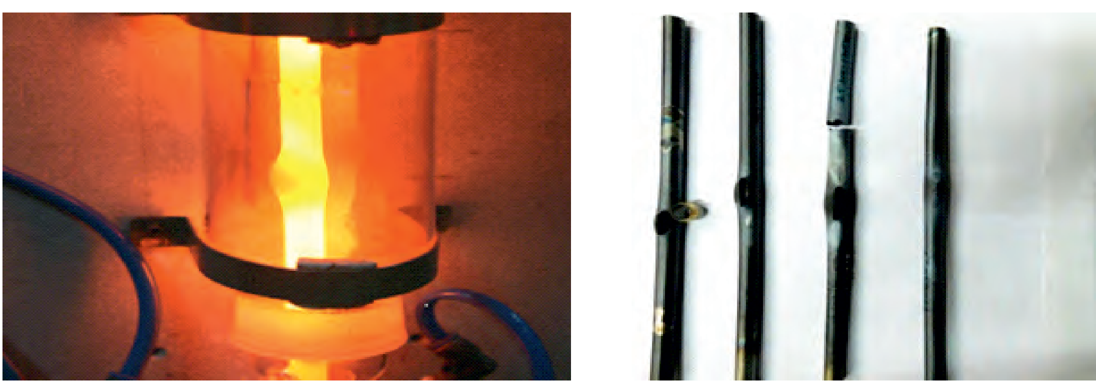

Fig. 17: Clad High Temperature Burst and Thermal Shock Shattering Tests. These tests are required to arrive at fuel failure criteria following design basis and postulated severe accidents in nuclear reactors. The above tests are for clad of Indian PHWRs. High temperature tests (up to 1200^{o}C) are for simulating power rise following Loss of Coolant Accidents (LOCA) and shattering tests are to assess clad structural integrity under thermal shock following cold injection of water from Emergency Core Cooling System (ECCS). Till date more than 200 numbers of such tests have been performed. These studies formed basis of Indian clad specific failure data required for severe accident safety assessment

7. Development of New Fuels and Fabrication Technologies

It was realized that the huge demand and growth expected for nuclear power in India can only be met through use of metallic fuels in fast rectors which promise high breeding ratio and lower doubling time. Hence R&D related to development of fast reactor fuels based on metallic fuels viz ternary U-Pu-Zr and binary U-Pu alloys was started at BARC, Trombay. In fact ternary metallic fuel is undergoing irradiation test at Fast Breeder Test Reactor (FBTR) to understand the irradiation characteristics. Development of metallic fuel is extremely beneficial for Indian fast reactor programme because of the impressive breeding ratio as compared to uranium-plutonium mixed oxide fuels.

New technologies in fuel fabrication are under development for handling nuclear materials having high radiation dose. Such situation will arise in at least two cases; firstly when plutonium recycled after from Fast Breeder Reactors has to be handled for further fuel fabrication. After each recycle the radiation does will increase owing to accumulation of Pu-240 isotope. Secondly important situation arises when U-233 transmuted from Th-232 has to be utilized for fabrication. In such cases small amount of U-232 is invariably generated and its concentration increases with burn-up. The decay chain of U-232 produce hard gamma photons (energy = 2.6MeV) which poses radiological safety challenges in fabrication of fuels using such materials. Activities are under way for developing automated remote handling facilities for fuel fabrication.

8. Discussion and Conclusions

This article covered the historical development of nuclear fuel in BARC. The fuel for India's first reactor that is, APSARA, was imported, thereafter massive research and development programmes were launched and several facilities related to fuel fabrication were created. The result is that fuel for all research and power reactors, built by India, were developed and / or fabricated by BARC and NFC. Some of the rare fuels fabricated are: uranium-plutonium mixed carbide fuels for FBTR, U-233 based fuel for KAMINI reactor. Specialists in uranium and plutonium metallurgy have undertaken systematic approach and successfully developed different routes of fabrication for different fuels being used in reactors or undergoing test irradiation.

Necessary facilities and expertise has been created for fabrication of plutonium based fuels required for successful execution of second stage of nuclear programme. In fact, India is among few countries to master plutonium fuel fabrication. Active research and development is underway for metallic fuel fabrication for future fast breeder reactors. This step is essential for movement towards third stage of the nuclear programme and our self-reliance even with limited reserves of uranium.

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