Nuclear policy: Are nuclear fuels for peaceful, safer co-generation and environmentally benign applications?

Necessitates trust from other side after Corona pandemic.

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Abstract

Here, safer nuclear fuels which can sustain in the high temperature and neutron fluence environment of the reactor core are investigated to utilize nuclear energy peacefully. At Nuclear Fuel Complex in Hyderabad, nuclear fuels are being manufactured which are best suited for the high temperature and fluence environment of the reactor core even in accidental scenarios. In this paper, nuclear fuels manufactured at NFC, Hyderabad are presented. The developed nuclear fuels have higher equivalent hydraulic diameter and breeding capability to produce U⁰²³³. Nuclear fuels having higher equivalent hydraulic diameter reduce the reactor core temperature substantially. These fuels have negative temperature coefficient of reactivity. Thus, in case of an accident, the fuel temperature never exceeds the safety limit. Therefore, the thermal heat available across the secondary of a heat exchanger can be utilized for different industrial processes. This allows the development of key technologies, such as safer co-generation of electricity and Hydrogen. The Three-Stage Indian Nuclear Power Program developed at BARC has been explained that eliminates loopholes from NPT and avoids buildup of stockpiles of Uranium, Plutonium. The safely produced Hydrogen gas has been utilized in many ways for different environmentally benign applications. Moreover, the processing of iron ore with the energy obtained from the IHX secondary side, eliminates the burning of coals and CO₂ emissions into the environment. Several radioisotopes have been developed and used for medical applications from spent fuel.

Keywords: Annular Fuels; Nuclear Fuels; Automated Systems; Crystallography

1. Introduction

One of the important safety requirements for a nuclear reactor is lowering the operating temperature of the reactor core. The higher operating temperatures of nuclear fuels can lead to melting of the reactor core in case of an accident. The conventional nuclear fuel pins which were used at Fukushima Daichi nuclear power plant make use of cylindrical fuel pellets that could not satisfy safety criteria set by Atomic Energy Regulatory Board (AERB). Here, nuclear fuel designs have been put forward, which are useful for cogeneration of electricity and process heat. In this paper, the necessity to use safe nuclear fuels for advanced nuclear power plants has been explained in section 2 with the help of major accidents that occurred in history. Section 3 describes the necessity of nuclear energy with safer fuels. Section 4 provides the nuclear fuel manufacturing process. Section 5 & 6 describe nuclear materials used in the reactor and design for nuclear fuels with their advantages. Section 7 provides choices of coolant used for power plants. Section 8 delineates some safety and stability issues envisaged for the nuclear power plant. Section 9 explains the peaceful usage of nuclear energy with the three-stage recycling method. Section 10 and 11 describes the recycling method and peaceful applications developed from nuclear energy, respectively. Section 12 signifies nuclear security issues and Global Centre for Nuclear Energy Partnership. Finally, section 13 draws the conclusions.

2. Highlights of major accidents

In the past, several reactor accidents were observed. These nuclear accidents have devastated many innocent lives and destroyed the environment. Out of the number of nuclear accidents, three major nuclear accidents which occurred in history are analyzed and briefly explained in the following subsections.
2.1. RBMK at Chernobyl

The Chernobyl nuclear disaster that occurred in the midnight of April 26, 1986 is illustrated below in Fig.1.

![Fig. 1: Chernobyl Reactor Core [1].](image1)

![Fig. 2: Chronology.](image2)

The reactor core built at Chernobyl was a graphite-moderated pressure tube or channel type BWR core. The chronological sequence of events for the accident at Chernobyl has been explained (Fig. 2) in details by Kushal [2]. Some of the peculiar facts that lead to Chernobyl accident are mentioned below:

1) The Chernobyl reactor core was operated in an over-moderated region with positive coefficient of reactivity. Thus, overheating of the reactor coolant caused an increase in the fraction of steam void that further led to a large amplitude step increase in reactivity.

2) The introduction of a sufficient number of neutron absorbers control rods inside the core would have made the positive void coefficient of reactivity less positive or even taken the reactor in the un-moderated region.

3) The Chernobyl RBMK core was a large diameter core with different parts of the core decoupled from one another. This caused controlling reactor power distribution difficulty at low power when a small fraction of the control rod is inserted into the core (Fig.1). The ensuing positive void coefficient of reactivity triggered two neurotics pulses (of length 4s) which eventually raised normalized reactor power by 2000 times. The prompt fission energy liberated after the accident can be calculated with following equation

\[
\frac{dn(t)}{dt} = n(0) \frac{K_0 - \beta}{A} \text{.}
\]

Here, \( A \) is called neutron regeneration time \( = 0.064 \text{ms} \) and is known as effective delayed neutron fraction [3]. The simulation studies by Fletcher et al. revealed that reactivity jumped rapidly to \( \sim 1.5 \text{s} \) at the highest power level during the transient [4]. This is due to the rise in positive void coefficient reactivity value by 20-30 pcm after insertion of control rods which introduced the negative temperature coefficient of reactivity. The solution of equation (1) with an initial value of \( n(0) = 200 \text{MWt} \) is

\[
n(t) = n(0) \exp \left( \frac{K_0 - \beta}{A} t \right).
\]

When peak power \( n(T) \) is 384 GW at \( T = 4 \text{s} \), the step change in reactivity from Eq. (2) would be \( K_0 = 1.2 \text{pcm} \) which is close to the estimate of \( K_0 = 1.5 \text{pcm} \) by H. Mochizuki¹ [5] analysis. By integrating equation (2) over the period of reactivity excursion, the total energy released after the power excursion can be estimated as,

\[
Q(T) = q(0) \frac{A}{K_0 - \beta} \exp \left( \frac{K_0 - \beta}{A} T \right) = 203 \text{GJ}.
\]

This is slightly smaller than the Soviet estimate of 239GJ [6]. The RELAP-5 simulations by Fletcher reveals the estimate of energy \( Q(T) \) as 169GJ, and power \( n(T) = 391 \text{GWt} \). But \( U_0 \) melts at an average energy density 1 MJ/Kg. Thus, the Chernobyl reactor core crossed the limit for melting the reactor core. Approximately, 95% of the molten reactor fell down to the bottom of the reactor core, and 5% of the fuel was shot upward from the fuel pins of the reactor core. With thermal to the mechanical conversion efficiency of 5%, a calculation shows that mechanical energy \( >0.5 \text{ GJ} \) would have lifted the 1000MG reactor shield blocks by 50m high up in the sky! This massive thermal explosion blew-up reactor cover assembly and relinquished the following large inventory of radioactive fission products into the open atmosphere as enlisted in Table 1 [7].

<table>
<thead>
<tr>
<th>Nuclide/Fuel</th>
<th>Release Fraction in %</th>
<th>Radioactivity (MCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nobel Gases</td>
<td>100</td>
<td>190±20</td>
</tr>
<tr>
<td>I(^{131})</td>
<td>55±5</td>
<td>45±5</td>
</tr>
<tr>
<td>Cs(^{137})</td>
<td>33±10</td>
<td>2.3±0.7</td>
</tr>
<tr>
<td>Sr(^{90}), Y(^{90})</td>
<td>4.0</td>
<td>2.8±0.8</td>
</tr>
<tr>
<td>Fuel</td>
<td>3.5±0.5</td>
<td></td>
</tr>
</tbody>
</table>

The radioactive lighter material was carried by wind in the parts of Ukraine, Belarus, Russia, Scandinavia and Europe. The consequences of this accident after the massive fire and a large amount of radioactivity release in the atmosphere are listed below:

1) Victims- 31 died, 500 hospitalized (out of which 203 people received >100 rem. dose)
2) 24,000 people, those who received radiation doses 35 to 50 rem each, were evacuated from the exclusive zone within the radius of 15 km from the plant.
3) 1,35,000 people were evacuated from an exclusive zone with a radius of 30 km.
2.2. PWR at TMI-2

In this accident which occurred in PWR at Three Mile Island (TMI), the peak fuel temperature in the second unit increased above 1273K, which initiated cladding oxidation exothermic reaction. This exothermic reaction released 6.5MJ/Kg of cladding material. With the following correlation, the mass of cladding oxidized per unit area exposed to steam at temperature T in time interval t can be determined as,

\[ W^2 = A e^{-\frac{R}{B}t}, \] (4)

where constant \( R \) is universal gas constant (8.314), \( A=294 \text{ kg}^2/\text{m}^4 \text{s}, B=167 \text{ MJ kg mol}^{-1} \). Consider the Zion PWR plant parameters. The total surface area of fuel cladding is 5400m². Assuming that the total surface area is exposed to steam for 5 minutes, will yield \( W=0.322 \text{ kg/m}^2 \), i.e. 1738.8 Kg of cladding material will be oxidized. Because two moles of Hydrogen are liberated per mole of cladding material, the mass of Hydrogen (\( \text{H}_2 \)) produced is \( M_{\text{H}_2} \) is 76.9 kg. A significant concern and fear developed among the public domain was that the Hydrogen bubble might ignite but this did not happen (Fig. 3).

![Fig. 3: TMI-2 Molten Core Configuration [8], [9].](image)

The TMI-2 accident scenario has been simulated with Melcor code [10]. The reactor coolant system pressure build-up for the first 6 periods is delineated in Fig. 4. A detailed analysis has been also performed by the Electric Power Research Institute [11].

![Fig. 4: Reactor Coolant Pressure Buildup History.](image)

The TMI-2 accident occurred due to ignorance whereas the Chernobyl accident occurred due to an intentional violation of the operating procedure. A similar incident took place in Davis-Besse plant also. Similarly, the Westinghouse built similar plants at Kori, a suburban village in Busan in South Korea has suffered station blackout (SBO) event on February 9, 2012.

2.3. BWRs at Fukushima Daiichi

At Fukushima Daiichi, a giant earthquake of Richter scale 9.0 followed within an hour by tsunami waves of 10 to 14 m struck the nuclear plant controlled by TEPCO on 11th March, 2011. At that time, the power plant site had unit 1, 2, 3 in operation and unit 4, 5, 6 in a refueling outage stage. These units were (Boiling Water Reactor) BWRs constructed by General Electric etc, which started operation between 1971 to 1979 with a power rating of 439 to 1067 MWe (Fig. 5). After the earthquake within a few seconds, all the three reactors were shut down by using control blades. The earthquake also disrupted the electrical power supply from the external grid. Moreover, the diesel generators stopped functioning after the tsunami waves hit the Fukushima Daiichi power plant, which eventually led to SBO event. After the failure of the reactor core isolation cooling system, TEPCO plant workers decided to inject seawater into the reactor core. Because of the delay in the injection of seawater into the reactor core of unit 1, unit 2, unit 3, some segments of the fuel rod were exposed without the presence of coolant which caused overheating of the fuel rods.
It has been postulated that the reaction in reactors Unit 1, 2 and 3 produced 800 to 1000 kilograms of Hydrogen gas per unit. The pressurized Hydrogen gas was vented out of the reactor pressure vessel. Thus, the Hydrogen gas got mixed with the ambient air and subsequently reached explosive concentration limits in Units 1 and 3. Moreover, piping connections between Units 3 and 4 caused passage of generated Hydrogen from Unit 3 to Unit 4. Additionally, the same dissociation reaction was occurring in the spent fuel pool (SFP) in Unit 4. Thus, Unit 4 was also filled with Hydrogen, resulting in an explosion. In comparison with TMI-2 accident, in Fukushima accident, the amount of radioactivity released was higher due to Hydrogen explosion at secondary containment and suppression pool.

As a consequence of the accident, total 4,00,000 people were evacuated; 1,60,000 people were from within 20 km exclusive zone. The number of deaths (around 1,700) those occurred are attributed to stress, fatigue and hardship of living as evacuees. Since the accident, the radioactive water has been flowing into the ocean. The Unit 1 at Fukushima has been discharging radioactive water at a rate of around 2 billion becquerels per day endangering aquatic life surrounding Japan and other parts.

3. Necessity of nuclear energy and safer nuclear fuels

According to international energy outlook, world energy consumption will grow from 524 quadrillion British unit (Btu) to 820 Btu between the years 2010 and 2040, i.e. rise of around 56%. The top three countries in the coal productions are China, America and Australia. Moreover, the top three countries in the crude oil productions are Saudi Arabia, America and Russia. In 2017, the top three natural gas producers are America, Russia, Iran [12]. Envisage the combustion of natural gas; pollutants, such as Carbon dioxide (CO₂), Carbon monoxide (CO), nitrogen oxides (NOx), Nitrous oxide (N₂O), volatile organic compounds (VOCs), particulate matter (PM), and trace amounts of Sulfur dioxide (SO₂) are released into the environment. Eventually, this will lead to total estimated increase in CO₂ emission by 40%, thereby causing global warming. It is true that Industrialization processes are polluting the atmosphere of the earth. Gases such as Carbon dioxide, Nitrogen dioxide etc. are causing a greenhouse effect. As a result, global warming is taking place. Gases like Sulphur dioxide are giving rise to acid rains. Metropolitan cities are becoming a jungle of concrete; therefore there is the necessity of small modular reactors for the development of isolated villages. The process of industrialization can’t be stopped because it is necessary for the development of mankind. It is creating job opportunities for people. These jobs are necessary for their survival. If this industrialization is creating problems, remedies to these problems are necessary.

The solar and wind are unsteady and unreliable, very low energy density sources of energy, therefore they have very poor availability factor with significantly lower plant efficiencies. Also, during the rainy season, the power conversion systems have substantially reduced output with very lower efficiency. It has been investigated that the performance of vertical axis wind turbines (VAWT) is deteriorated seriously in different rain conditions [13]. According to the principle of conservation of energy, these sources of energy are incompatible for industrial load demand where 24 hours of operation is required. In many engineering applications, the amount of energy converted per unit time in Watts is significantly important. Few light elements such as Deuterium, Tritium, as well as Helium-3 are used as fusion fuel but there is no sustainable fusion reaction for more than few minutes yet. Therefore nuclear fission becomes an inevitable source of clean energy.

Also, several peaceful scientific activities are going on in Antarctica. These places experience six months of daylight and six months of darkness. The lowest temperatures measured lies from -92°C to -98°C. In order to continue scientific experiments at these difficult places, electricity is required which is expected to be generated from a very small capacity modular nuclear reactor.

Nuclear energy is the most suitable and clean source of energy. It plays a vital complementary role to other low energy density sources of energy. Nuclear fuels have a high calorific value. One ton of natural uranium can produce more than 40 million kilowatt-hours of electricity. This energy is equivalent to about 80,000 barrels of oil or 16,000 tons of coal. Without production of carbon dioxide, advanced nuclear power plants have (20-25%) higher efficiency than conventional plants which make use of fossil fuel. Nuclear energy is used as process heat source for industrial processes such as continuous mass production of hydrogen or extraction of bitumen from the shell. The Nuclear Power Plants (NPPs) can supply large scale electrical power at a reasonable price as a full-time available base-load to electrical grids without polluting the environment. Nevertheless, safety has been a primary concern because of the potential release of radioactive materials from an accident site. Although safety precautions were implemented, there have been major accidents, such as Three Mile accident, Chernobyl accident and recent Fukushima accident. Therefore, both industry and regulators from India are re-analyzing safety aspects for NPPs and have taken a number of measures to address challenges raised from these accidents.

Compare to Uranium reactors, far less radioactive waste quantities are produced by Thorium reactors and these wastes are less shorter-lived and radioactive. Therefore, nuclear fuels developed from Thorium are environmentally benign. India has one of the largest reserves for Thorium. The three stage recycling method enables development of several applications from Thorium fuels.
AERB has set new requirements to be satisfied by nuclear fuels to overcome the accident scenarios. These requirements have been satisfied by designed nuclear fuels. The design flow from mining to the testing of these safe nuclear grade fuel elements has been explained in the following sections.

4. Uranium mining and fuel manufacturing

In India, the mining and processing operations for Uranium ores are performed by the Uranium Corporation of India Ltd. (UCIL). Some of minor Uranium resources within India are illustrated below in Fig. 6.

![Fig. 6: Minor Uranium Resources as Pointed within India. Source: www.forbes.com](image)

4.1. Uranium investigations with ground survey

Recently, reconnaissance (5,432sq km) and detailed surveys (282.75sq km) helped in finding the following promising Uranium anomalies of known occurrences in various geological environs:

a) Siwalik Group, Una district, Himachal Pradesh: Sandstone at Gwalsar-Parah.
b) Mahadek basin, East Khasi Hills district, Meghalaya: Sandstone at Laitdih.
c) Motur Formation, SatpuraGondwana basin, Betul district, Madhya Pradesh: Sandstone at Dharangmau.
d) Betul Crystalline complex, chhidwara district, Madhya Pradesh: Brecciated quartz reef / vein ingranite near Bijori, Bhuli, Khudhradhana, Setparas and Sajba.
e) Rohil and its extensions, Sikar district, Rajasthan: Albite zones in Rohil Central western extension, Gumansinghki Dhanii, Narsinghpuri and Jaha areas (Fig. 7).
f) Bortalao Formation, Rajnandgaon district, Chhattisgarh: Gritty sandstone and conglomerate of Bortalao Formation along Kolarghat-Kauhapani- Gandhinagar, Bortalao-Khampura-Burhanchhapar and Nawatola-Ramatola-Kolarbhatti tracts.

![Fig. 7: Exploratory Mining Site at Rohil Uranium Deposit, Sikar District, Rajasthan [14].](image)

The processing of geophysical data of Dungarpur Block in Aravalli Fold Belt, Rajasthan has resulted in the identification of eleven potential target zones around Undwala, East of Tartai & ChhotiMandli, Lasara, Bachi-fala & Sarangi, Parsola, North of Parsola, East of Manpur, North of Bhabrana, South of Jambura, Pavati-Burel and Salumber and some other sites in Madhya Pradesh (Fig. 8).
However, these Uranium resources are very insufficient for growing energy demand.

4.2. Processing of uranium ore

The Fig. 9 shows nuclear grade yellow cake and impure CSDU. During the processing of secondary source of U, the Crude Sodium Diuranate obtained, contains impurities such as iron (10%) and rare earths (5%). An extraction process selectively extracted impurities including rare earths remained in the aqueous phase while U into the organic phase.

4.3. Manufacturing of Nuclear fuels

The Nuclear Fuel Complex (NFC), at Hyderabad, a constituent unit of Department of Atomic Energy (DAE) is engaged in the production of natural Uranium oxide fuel bundles for PHWRs, and fuels for other types of reactors, Reactor Core Structural, Reactivity Control Mechanisms and special materials like Tantalum, Niobium etc. In addition, NFC produces fuel cladding tubes and other critical components like all the core sub-assemblies, Hexagonal wrapper tubes etc., made out of special materials e.g. stainless steels for Fast Breeder Reactors. Also, NFC has been manufacturing Stainless Steel Tubes/ Pipes, MDN-250, MDN-350, MDN-59, SuperNi-42 tubes, Nimonic-75 tubes, and Titanium alloy products for critical application in Reprocessing Plants, Nuclear Power Plants, and Space establishments. A rapid scanning machine for scanning the fracture or manufacturing fault in fuel elements used at NFC is shown in the Fig. 10. This will ensure that UO₂ pellets stack and fit well in fuel pins without any cracks. The machine also acts as a tube feeding and butting system.
NFC has successfully logged record numbers for each fuel pellet, fuel bundles which have met the safety requirement. All the indigenous raw material in the form of DU/HTUP/SU received from M/s UCIL and spent fuel from IGCAR are converted into fuel rods in order to fulfill the requirement of nuclear fuel cycles.

5. Nuclear materials

Nuclear Fuel Complex has come up with safe fuel designs which are best suited for operation during any accident scenarios. The Table 2 enlists some of the materials used in PWR cores and their corresponding cross-section in thermal energy range.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Sigma_p$ (cm$^{-1}$)</th>
<th>$\Sigma_f$ (cm$^{-1}$)</th>
<th>Relative Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>$1.8 \times 10^{-2}$</td>
<td>0</td>
<td>0.053</td>
</tr>
<tr>
<td>O</td>
<td>$7.15 \times 10^{-3}$</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fe</td>
<td>$9.44 \times 10^{-4}$</td>
<td>0</td>
<td>0.026</td>
</tr>
<tr>
<td>U$^{235}$</td>
<td>$3.05 \times 10^{-4}$</td>
<td>0.146</td>
<td>0.602</td>
</tr>
<tr>
<td>U$^{238}$</td>
<td>$6.98 \times 10^{-3}$</td>
<td>1.19$\times 10^{-2}$</td>
<td>0.091</td>
</tr>
<tr>
<td>Core total</td>
<td>$3.62 \times 10^{-2}$</td>
<td>0.1569</td>
<td>1.000</td>
</tr>
</tbody>
</table>

6. Illustration of some safer fuels and reactor core building blocks from NFC, Hyderabad

The combination of nuclear fuels with different moderator materials has several advantages over conventional fuel. If $u$ is lethargy gain, then the probability for collision of a neutron for different materials is given as,

$$ P(u' \rightarrow u) = \frac{e^{u'-u}}{(1-a)} \text{for } u - \ln\left(\frac{1}{a}\right) < u' < u, $$

$$ 0 \text{ otherwise,} $$

where $a$ is defined as $\frac{(A-1)^2}{(A+1)^2}$. Therefore average gain in the lethargy ($\overline{\Delta u}$) is given as,

$$ \overline{\Delta u} = \int_{a}^{1} \Delta u P(u' \rightarrow u) du'. $$

The effect of different moderators such as $^{9}$Be, $^{12}$C, $^{23}$Na, $^{207}$Pb, $^{232}$Th, $^{238}$U with nuclear fuels have been studied while making the reactor core critical. The number of collisions required to thermalise a neutron from 2 MeV to 1 keV in these moderator materials have been plotted in the Fig. 11. Thus, the number of collisions required to reduce the neutron energy from 2 MeV to 1 keV increases linearly with atomic mass $A$.

![Fig. 11: Number of Collisions Necessary to Slow Down Neutron from 2 Mev to 1 Kev Energy.](image)

The interaction rate of neutrons with atoms of material having mass number $A$ is denoted with $F$. The first order collision density ($F_1$) denotes the collision density that all the source neutrons need one collision to reach $dE$; $F_2$ indicates collision density that all the neutrons need two collisions to reach $dE$ and so on (Fig.12). If neutron source of strength $S_0$ emits neutrons of energy $E_0$, the expressions for $F_1$ and $F_2$ are given below:

$$ F_1 = \frac{S_0}{E_0(1-a)} \text{for } aE_0 < E < E_0, $$

$$ = 0 \text{ for } E < aE_0, $$

$$ F_2 = \frac{S_0}{E_0(1-a)^2} \ln\left(\frac{E}{aE_0}\right) \text{for } aE_0 < E < E_0, $$

$$ = \frac{S_0}{E_0(1-a)^2} \ln\left(\frac{E}{a^2E_0}\right) \text{for } a^2E_0 < E < aE_0, $$

where as $F_3$ is obtained from $F_2$ and the expressions for third order collision density ($F_3$) is given below:
\[
F_3 = \frac{S_0}{2E_0(1-a)^2} \ln^2 \left( \frac{E}{E_0} \right) \text{For } \alpha E_0 < E < E_0, \quad (11)
\]
\[
= \frac{S_0}{E_0(1-a)^2} \left\{ \ln \left( \frac{E}{E_0} \right) \ln \left( \frac{E}{E_0} \right) + \ln \left( \frac{\alpha E_0}{E} \right) \ln \left( \frac{E}{\alpha E_0} \right) \right\} \text{For } \alpha^2 E_0 < E < \alpha E_0, \quad (12)
\]

Also,
\[
F_3 = \frac{S_0}{2E_0(1-a)^2} \ln \left( \frac{E}{E_0} \right) \text{ for } \alpha^3 E_0 < E < \alpha^2 E_0. \quad (13)
\]

When \( E > \alpha^3 E_0 \), in asymptotic energy region, the collision density function \( F \) becomes smoother and attains the value \( \frac{S_0}{\Delta \varepsilon} \). The Fig. 12 shows the first, second and third order neutron collision densities for unit source of 2 MeV neutrons in \( Th^{232} \).

Several eutectics which are a mixture of different moderator materials have been developed at BARC. The cross-section library database from Nuclear Data Physics Centre of India (NDPCI) at Bhabha Atomic Research Centre (BARC) has been used to find out criticality parameters for the reactors. The study has revealed that the compound nucleus formation and neutron production time is approximately \( 10^{-22} \) seconds for different nuclear reactions. The neutron clock has been used to determine pre-fission time from measured pre-fission neutron multiplicity values. The compound nuclear formation time is determined by measurements of pre-fission multiplicity for two different entrance channels forming the same compound nucleus \( C^{248}_f \) having different entrance channel dynamics [15].

6.1. Nuclear materials and fuel shapes manufactured by Nuclear Fuel Complex

As the capture cross-section is high in resonance energy range, moderators such as \( U^{238}, Th^{232} \) upon capture of neutrons are converted into fissile material, thus breeding of new fuel takes place. The NFC has been manufacturing different types of fuels with different shapes for the safer operation of fuel even during the accident scenarios. The stress tests performed on nuclear fuel elements and blocks (Fig. 13 - Fig. 19) guarantees that there will not be any mechanical failures during severe accidents.

For high temperature reactor operation (\( T_c \sim 1000^\circ \text{C} \), the BISO (Bi-structural isotropic) or TRISO (Tri-structural isotropic) fuel elements are embedded inside either the fuel compacts or pebbles (Fig. 13, Fig. 14). In TRISO particles, the fuel kernel (\( UC_2+ThC_2 \)) is surrounded by three high density carbon layers following low density pyrolytic carbon (Fig. 13 and Fig. 14). Although, TRISO coated particle fuel can withstand in the very high temperature environment of 1600°C without failure, a high-temperature gas-cooled reactor (HTGR) at Fort St. Vrain in United States is permanently shut down due to electrical, corrosion, and many other issues within few years. The Innovative High Temperature Reactor (IHTR), overcomes water infiltration as well corrosion issues at high temperature conditions. The IHTR-A makes use of fuel in the form of pebbles in which TRISO particles are embedded inside Pebbles. According to crystallographic analysis, the average void fraction among the pebbles to attain the criticality is about 0.4. For High Temperature Reactor operation, the TRISO particles can be also embedded inside the fuels illustrated in the Fig. 14 to Fig. 18. Ceramic material has been selected for the construction of Indian reactor cores.

\[
\begin{align*}
\text{(UD+ThC) Kernel} & \quad \text{Low Density Pyrolytic Carbon} \\
\text{Inner High Density Pyrolytic Carbon} & \quad \text{Carbide} \\
\end{align*}
\]

Fig. 13: Tristructural-Isotropic (TRISO) Particle Element.
The functions of TiC interlayer in spherical TRISO is described below:

The TiC interlayer is used to retain all the gaseous fission products released from the kernel hence, it functions as a pressure vessel. Moreover, TiC also functions as a diffusion barrier for metallic fission products.

For low temperature reactor operation fuel elements are used (Fig. 15-Fig.19) without TRISO particles. For low temperature reactor fuel, the UO₂ powdered fuels are sintered and stacked inside the fuel package. The fuel elements (Fig. 15-Fig.19) inserted into the fuel blocks (e.g. Fig. 20), are cooled directly or indirectly through a moderator.

The American reactor CP (Chicago Pile) makes use of nuclear fuel somewhat similar to fuel shown in the Fig. 17, however, could not be run successfully for prolonged operation. The fuel in Fig. 17 has unique construction. The first research reactor in Asia (Apsara) became operational in Bhabha Atomic Research Centre in August 1956. The reactor was decommissioned in 2009, after providing more than five decades of dedicated service to the researchers. A swimming pool type research reactor "Apsara-upgraded", of higher capacity was born on 10th September 2018 at 18:41 hrs, sixty-two years after Apsara came into existence. The indigenously developed reactor uses plate type dispersion fuel elements made up of Low Enriched Uranium (LEU).

The annular fuels shown in Fig. 18.a and Fig. 18.b can be directly or indirectly cooled through moderators available. The Annular Fuels (Type 1) have multiple moderator rings around the central region like spherical TRISO particles for safety purpose (Fig. 19). Like TRISO fuel described earlier, the multilayered annular fuels have superior proliferation resistance attributes. The high temperature and neutron fluence grade cladding material acts as a fission barrier. All these nuclear fuels are manufactured at Nuclear Fuel Complex, Hyderabad considering all the other safety perspectives. Due to large heat transfer surface area, the fuel temperatures are dropped substantially. This reduces Hydrogen generation and reactor core melt risks in case of accidental scenarios.
Some of the functional requirements that have been established by these reactor fuels are described below:

1) At BARC nuclear fuels have been developed with various interlayers e.g. TiN, TiC, ZrC, etc. to prevent potential release of radioactive materials. These safe fuels are capable of generating the required power with negative fuel temperature coefficient for the required exit burn-up.

2) The developed fuel retains all types of fission products; therefore there is no leakage or release of radioactive materials into the primary coolant.

3) The developed fuels help in minimizing parasitic neutron capture.
4) The fuel tube and fuel compact locations are maintained in the core, thus basic nuclear and thermal-hydraulic requirements are satisfied (Fig. 21).
5) The fuel tube directs reactor coolant through the core to the outlet with required flow distribution so that the heat transfer performance requirements are met during all modes of reactor operation or transient.
6) The core structural oppose material damage caused by irradiation-induced effects.
7) During the anticipated operational occurrences or normal operation, the mechanical design of fuel assures that fuel damage is improbable.
8) Safe handling, shipping, as well as core loading of the fuel is possible.

6.2. Properties and experience with Nitride fuels

It has been experimentally found that reactor fuels in the form of U3Si2 and UN-U3Si2 have higher thermal conductivity than that of fuels in the form of UO2 and UO2-BeO. Fuels in the form of UN have higher thermal conductivity and uranium density thus promising candidates for chain reaction, nonetheless they are susceptible corrosion and oxidation. The Table 3 enlists some of the properties for these fuels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UO2</th>
<th>UO2-BeO (10%Vol BeO)</th>
<th>U3Si2</th>
<th>UN-U3Si2 (30% Vol U3Si2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture Stress [MPa]</td>
<td>~105</td>
<td>~105</td>
<td>~250</td>
<td>~250</td>
</tr>
<tr>
<td>Linear Thermal Expansion [K⁻¹]</td>
<td>1.05 × 10⁻⁵</td>
<td>1.05 × 10⁻⁵</td>
<td>9.38 × 10⁻⁶</td>
<td>1.53 × 10⁻⁵</td>
</tr>
<tr>
<td>Thermal Conductivity [Wm⁻¹K⁻¹]</td>
<td>3.55</td>
<td>-5.58</td>
<td>14.98</td>
<td>-19.18</td>
</tr>
<tr>
<td>Metal Density</td>
<td>9.66</td>
<td>8.74</td>
<td>11.30</td>
<td>12.92</td>
</tr>
<tr>
<td>Theoretical Density</td>
<td>10.95</td>
<td>10.08</td>
<td>12.25</td>
<td>13.66</td>
</tr>
<tr>
<td>Elastic Modulus [GPa]</td>
<td>~204</td>
<td>~205</td>
<td>~118</td>
<td>~262</td>
</tr>
<tr>
<td>Specific Heat [Jkg⁻¹K⁻¹]</td>
<td>245</td>
<td>245</td>
<td>208</td>
<td>206</td>
</tr>
<tr>
<td>Melting Temperature[°C]</td>
<td>~2800</td>
<td>~2800</td>
<td>~1665</td>
<td>~2800</td>
</tr>
</tbody>
</table>

Therefore, fuels in the form of UN-U3Si2 were developed to overcome the issue of corrosion and oxidation. By comparing various parameters in Table 3 for various types of fuels it can be deduced that UN-U3Si2 fuels have the most desired thermo-physical properties among four fuel compositions.

In order to reduce fission gas release, fuel temperature & SiC cladding failure risk, UN-U3Si2 fuel was found to be the best choice. An effective approach to reduce stress-induced failure risk, the fuel temperature, pellet-clad mechanical interaction and fission gas release is to increase the fuel thermal conductivity. UN fuels have a lower creep rate, higher fracture stress & higher modulus, as a consequence nitride fuel is vulnerable to Pellet-Clad Mechanical Interaction (PCMI) induced failure and cracking which can lead to severe issues as depicted in the Fig. 22.
This type of problem is handled by the reduction in UN fuel density to 80-85% of the theoretical density. Similarly, the density reduction was considered for UN-\(U_3Si_2\) fuel to avoid PCMI-induced failure and cracking.

Reducing the fuel temperature and fission gas release by using annular fuels (Fig. 18) is an interesting solution which has been investigated by K. Umasankari, P. Vijayananet. al [16].

The silicon carbide (SiC) has good performance with regard to oxidation resistance, neutron economics and irradiation stability for accident tolerant fuel cladding. The loss of the tubing hermeticity and cracking of the SiC matrix caused by the brittle nature of the SiC puts a limitation on engineering application of SiC cladding.

Therefore, additionally, TiC and TiN are invented and selected as alternative cladding material at BARC.

In order to prevent the worst case partial core melt scenario (e.g. that of for PWR in TMI-2) with Hydrogen generation reaction, annular fuel with multi-layered coating has been used (Fig. 19).

Pump failure scenario has been observed in Canadian reactor too. Therefore, innovative GEN IV reactors are being developed in India, which make use of the fuel elements shown earlier (Fig. 13-Fig.19) for different reactors for a range of reactor power levels. These reactors have several unique features e.g. advance recirculation buoyancy pump systems [17, 18]. Thus, core melt risks are eliminated due to pump failure.

The low temperature reactor core compatible nuclear fuels without TRISO particles (described earlier in Fig.15 to Fig.19) have larger heat transfer areas. These fuels have higher values of equivalent hydraulic diameters which enables better heat transfer with the coolant. Thereby these fuels have substantially lower temperatures in the reactor core even during accident scenarios such as loss of coolant accident (LOCA). This eliminates Hydrogen production and core melt possibilities in the reactor core in case of accidental scenarios.

7. Coolant choice
The coolants that can be used to remove the heat from inside the reactor core must have the following good characteristics:

1. It should perform cooling operations in the operating temperature range.
2. It should have radiolytic stability in a high radiation environment (for primary coolant only). The coolant should have a low freezing temperature, preferably lower than 525°C for metal coolant.
3. The coolant should have large sufficient thermal inertia and thermal conductivity.
4. It should have low vapor pressures (substantially less than one atmosphere) at operating temperatures, thus not volatile.

The molten salts seem to be excellent candidates which satisfy most of these requirements. There is no single molten salt which satisfies the requirement of low melting temperature; therefore multi-component eutectic mixtures are needed. There are some multi-component eutectic salt mixtures that satisfy the criteria of melting temperatures less than 500°C. The multi-component mixtures usage ensures compositional and phase stability.

Some of the coolants that have been used earlier are enlisted here e.g. Helium, Nitrogen, CO\(_2\), Air, Light water, Heavy water, ZrH, Sodium, Lead Eutectics, LiF–NaF–RbF, LiF–NaF–BeF\(_2\), NaF–BeF\(_2\), LiF–RbF, 2LiF–BeF\(_2\), LiF–NaF–ZrF\(_4\), LiF–BeF\(_2–ZrF_4\), LiF–NaF–KF, NaF–ZrF\(_4\), LiF–ZrF\(_4\), KF–ZrF\(_4\), RbF–ZrF\(_4\).

8. Application of safer fuels for innovative reactors
GEN IV reactors are being developed with inherent safety features at BARC. This section briefly outlines the innovative Indian innovative GEN IV reactors which make use of invented safer nuclear fuels (described in the Section 6).

8.1. High temperature gas cooled reactors
The Very High Temperature Reactors (VHTRs), are being developed as a part of Gen-IV reactors (3rd stage of Indian Program). This VHTR is also called high temperature gas cooled reactor (HTGR), which is cooled with Helium gas. This graphite moderated reactor has been designed with the goal of higher coolant outlet temperature so as to support high temperature chemical processes such as the production of Hydrogen with thermo-chemical processes. The VHTR enables the cogeneration of electricity and process heat. Using the process heat from the reactor, the Hydrogen production plant, as well as other industrial process heat applications can be built up. The VHTR produces Hydrogen from water by using electro-chemical, thermo-chemical or hybrid processes.

The Innovative High Temperature Reactors (IHTR A, B & C) are thermal power reactors developed initially with power level (about 600 MWt) having feature that allows removal of decay heat by no external means. Generally, high temperature reactors make use inert Helium as coolant and graphite as moderator. However, Indian designs differ especially with regard to coolant, fuel as well as moderator. In IHTR, the emphasis has been given to advance recirculation buoyancy pumping system leading to use of lead eutectic alloy and molten salt based coolants.

Several Hydrogen production cycles are envisaged for sustainable Hydrogen production. The different Hydrogen production processes require heat at different temperatures 823 K (for Copper-Chlorine process) and greater than 1123 K (for Sulfur-Iodine process). A decision has been taken to accomplish Hydrogen production at higher temperature with reactors operating at 1273 K. The efficacy of IHTR to operate at a higher temperature facilitates Hydrogen production with higher efficiencies. The higher operating temperature of the IHTR is also well suited for electricity generation with high efficiency. For the electricity generation with high efficiency, the development of the Brayton cycle with CO\(_2\) has been in progress.

A modified pebble bed advanced high temperature reactor modeled at Ohio State University by Thomas has coolant flow upward and pebble flow in opposite (downward) direction from top to bottom [19].

The combinations of TRISO fuel elements with fuels from Fig. 15 to Fig. 18 are suitable in very high temperature reactor cores. The Innovative High Temperature Reactor (IHTR-A) makes use of fuel in the form of pebbles with TRISO particles embedded inside. The continuous refueling is one of the advantages for IHTR-A (Fig.23).
An accident scenario that models intentional withdrawal of the control rods, thereby increasing the reactor power, fuel and coolant temperature have been shown in Fig.24 and Fig. 25. Due to negative Temperature Coefficient of Reactivity, the reactor power settles down (Fig.24) after 300 seconds. The worst case fuel temperature for TRISO particle fuel in a high temperature environment for this accident scenario is less than 1300°C (Fig.24, Fig. 25).

IHTR-B & IHTR-C are types of High Temperature Reactors with stationary fuel (Fig.26 and Fig. 27).

The IHTR-B makes use of stationary fuel in the form of hexagonal blocks (Fig. 26). The higher reactor operating temperature of the Innovative High Temperature Reactor (IHTR) is useful in industrial applications such as Iron processing, Hydrogen productions, etc. [22].
8.2. Molten salt breeder reactors

There has been great interest in the development of fuels in liquid form for Innovative Molten Salt Breeder Reactor (IMSBR). An experimental facility (Fig. 28) for molten salt reactors is developed at BARC. The Innovative Molten Salt Reactor (IMSBR) developed at BARC makes use of proliferation resistant $^{232}$Th fuel. Earlier investigation on the coolant for IMSBR accomplished during the 1970s included preparation of pure LiF and ThF$_4$ including the development of equipment, solubility of PuF$_3$ in LiF–BeF$_2$–ThF$_4$ mixtures, vapour pressure determination of materials of interest as well as thermodynamics of U–Bi alloys for IMSBR [23].
8.3. Sodium cooled fast reactors

These reactors are very complex and several accidents are observed all over the world with leakage of fuel radioactivity except India. Breeder reactors EBR-1 & Fermi operated by the United States were shut down due to partial meltdown in 1955 & 1966 respectively [24]. At Monju power plant in Japan, on December 8, 1995, several hundred kilograms of Na was leaked out and converted into fumes. The reactor is currently in decommissioning phase. Also, an accident with the experimental Sodium loop was observed with a burst at the research lab in South Korea, recently.

India has been operating Sodium cooled fast reactor since past several decades without any serious incidence. These reactors make use of a fast neutron energy spectrum to cause the fission. They are used to breed U\(^{233}\) from Th\(^{232}\) reducing Pu\(^{239}\) build-up. In these reactors, inflammable Sodium is used as coolant thus utmost importance is given to safety to operate such reactors. The development of Innovative Sodium Fast Reactors has been explained in more detail in the Section 10.

8.4. Lead cooled fast reactors

Sodium being extremely violent, the Lead has been used as a substitute coolant for fast reactor. The coolant Lead has a very high melting point (601K) which lead to solidification problems when the reactor is operated at low temperatures. Compared to Sodium, Lead is more corrosive to steel, hence Gas Cooled Fast Reactors have been devised.

8.5. Gas cooled high temperature fast reactor

Fig. 29 shows the cross section for Indian version of Innovative High Temperature Gas Cooled Fast Reactor core. Coolants such as supercritical CO\(_2\), Helium are selected for power conversion. In these reactors, the fertile Th\(^{232}\) has been used as blanket material. The higher coolant temperature (≈1000°C) along with Braytons cycle provides ≈ 55% efficiency.

8.6. Supercritical-water reactor (SCWR)

The critical temperature and pressure for the steam and water mixture are 647.14 K and 22.12 MPa, thus boilers that operate above the critical point generate supercritical fluid which is what used in the Supercritical-water-cooled reactor. The SCWRs are combinations of following two well established technologies,

i) Superheated fossil fuel operated boilers.

ii) Boiling water reactors (BWRs).

A version of AHWR developed by BARC is based on the SCWR concept.

8.7. Accelerator driven system

Parallel to sodium cooled reactors, in the second stage, accelerator-driven systems (ADS) have been developed with Plutonium and minor actinides. The accelerator driven system developed by BARC makes use of Thorium fuel inside the subcritical core of ADS which is bombarded by neutrons from a spallation source. Thus, ADS help in establishing and expediting equilibrium fuel cycles for third stage nuclear power plants. It also helps in burning the nuclear waste from 3rd stage of nuclear power plants.

8.8. Candle type reactor

In this reactor design, from one end of the reactor, the fission reaction zone moves to the other end with a constant velocity. The movable beam moves the neutron source axially.

Fig. 30 shows a fissile reaction zone that passes through the remaining part of the reactor core axially. Once the fuel is loaded, the burn-up wave travels from one end to another end with the time span of 40-50 years. This reactor is also known as a travelling wave reactor. Candle type reactor makes use of U\(^{233}\) and Pu\(^{239}\) fuels. Additionally, efforts have been pursued to integrate good properties of multi-layered annular fuel with candle light reactor. Long-life CANDLE reactors with thorium fuel have been investigated for the burn-up performances and the following observations are noted.
These types of reactors with Thorium fuel have a higher burn-up levels about 100 GWD/ton-HM. CANDLE reactors with thorium require about 15% enrichment.

Thus, thorium fueled CANDLE reactors are promising candidates for longer reactor operations with higher burn up performance. They are also employable for generation of electricity on the external planet.

9. Stable nuclear plant operation

At the THORP nuclear fuel processing plant, 160 kg plutonium and 20 tonnes uranium was leaked from a broken pipe in Sellafield, England. Several such reactor accidents have taken place in foreign countries including France where 20 reactors were found for example with seismic weaknesses. To overcome these accidents and for the stable, smoother and safer operation of the overall plant, some systems are used, some of which are enlisted here. These systems include (i) API controller (ii) THTDs (iii) Detectors (iv) Automation software. As it is not possible to explain each and every system, for brevity, here some of systems are described.

9.1. Axial profile index controller

During the reactor operation, several types of fission products are generated inside the reactor fuels which act as poison for the neutrons. These fission products imbalances the neutrons flux spatially. Subsequently, the disturbed neutron flux can create a hot spot at a particular position in the reactor core. This can raise the fuel temperature beyond the safety limit and cause partial core melt. Fig. 31 shows the build-up of normalized Xenon and Iodine concentration in the upper half of the reactor core on the X and Y-axis respectively whereas Z-axis indicates time in hours.

Therefore, for sustained and stable operation of the reactor core, an Intelligent Constrained Receding-Horizon Predictive Control has been developed that balances the neutron flux spatially eliminating flux oscillations. The growing neutron oscillations are intentionally generated at 30 Hours and killed at 60 Hours (Fig.32) by using Intelligent Constrained Receding-Horizon Predictive Controller.
The axial offset in the reactor power distributions should be maintained near to zero for the stable reactor operation. The value of axial profile index (API) in free running oscillations keeps on changing but when the controller is employed, the flux and power level in top and bottom zone are forced to be the same thus API goes to zero. Thus oscillations due to neutron poisons are completely eliminated (Fig.3).

The displacement of the axial offset control rods to eliminate the neutron flux oscillations in the lower half of the reactor core is shown in the Fig. 3. At the 30 hrs, the AO rods are intentionally disturbed in order to generate the neutron flux oscillations. This will lead to asymmetric buildup of Xenon and Iodine in the upper half and lower half of the reactor core. These flux oscillations are allowed to grow until 60 hrs. By using an Intelligent Constrained Receding-Horizon Predictive Controller, the oscillations are killed at 60 hrs without operator’s intervention.

**9.2. Thermosyphon heat transfer devices with their application strategies**

Thermosyphon Heat Transfer Devices (THTD) are deployable anywhere in the heater section or reactor core to remove the heat passively. These devices have been used in experimental reactors at BARC. Being passively operated, they have been used as decay heat removal systems. THTDs are incorporated within the annular fuel rods to remove the decay heat more effectively. In order to extract the decay heat by using THTDs, different strategies have been developed as shown in the Fig.34, Fig. 35 and Fig. 36. To remove large decay heat, a number of THTDs (array of THTDs) are inserted in the various types of reactor cores as shown in the Fig.34, Fig. 35 and Fig. 36.
The THTDs are mounted and inserted vertically. In case of loss of coolant accident in primary loop, the reactor core is cooled with THTDs passively. PHWRs are developed in the first stage of a three stage Indian power program (Fig. 34). The AHWRs from the third stage of the three stage nuclear power program, fuelled with Thorium fuels, make use of fuels in the annular form [16]. The THTDs are fitted within the annular fuels in the reactor core (Fig. 35).

Innovative Thermal Reactors (ITR) developed at BARC belonging to Generation IV reactors make use of THTDs in radial arrangement (Fig. 36). Instead of arranging the fuel bundles, it is also possible to arrange each fuel elements on the circumference of the circles with increasing radii.
Similarly, in case of Innovative Fast Reactor (IFR), the fuel elements are cooled indirectly through several holes in the moderator. Similar layout for THTDs is applicable in IFR.

Here, working of Thermosyphon Heat Transfer Device (THTD) has been explained. The generalized design for THTD includes unheated section, heated section, cooler section. The cross over device controls the flow regime of the fluid inside the THTD (Fig. 37). The THTD has an outer diameter $D_o$ and height $H$. The inner tube has inner and outer diameters $d_i$ and $d_o$ respectively in the heated section; the same are $d_{hi}$ and $d_{ho}$ in cooler section. The outer wall of the heated section is supplied with constant heat flux $q_h$ and the outer wall of the cooler section is in contact with secondary fluid having a mean temperature of $T_s$ (Fig. 38).

![Fig. 37: Model for THTD](image1)

Two types of THTDs are developed based on fluid flow. THTD-I liberates the heat with secondary flow in the counter current direction whereas THTD-II liberates heat with secondary flow in parallel direction. Here, the working of the THTDs is briefly explained by applying the conservation of mass, momentum and energy equations. The temperature distribution and the heat transport capability of each of the THTD are compared. It is found out that heat transport capability of the THTD-I is better than that of THTD-II.

### 9.2.1. Design analysis for THTD- I

The heat and mass transfer analysis for the THTDs are accomplished by using conservation of energy, mass and momentum equations over the system. THTD-I is filled with incompressible fluid in the close loop (Fig. 39). The first equation is conservation of momentum equation including frictional losses over the closed thermosyphon loop. The fluid mass flow rate is not dependent on the location of the fluid in the loop as indicated by the second equation. Insulating material is used to insulate the THTD to avoid heat exchange with the surrounding. The flow-rate of fluids during the steady state is simulated as a function of the heater power by solving conservation equations.

$$\frac{k_w}{A} \frac{\partial w}{\partial z} = g\rho_0 \beta T dh - \frac{f_{L_eff} W^2}{2D_p \rho_0 \mu^2}$$

(14)
\( \frac{\partial w}{\partial s} = 0, \)  

(15)

where, effective length taking into account the local losses is denoted by \( L_{\text{eff}} \) and the total length of the loop is denoted by \( L_t \). Thermal expansion of the fluid generally takes place, when the fluid is heated. The thermal expansion coefficient \( (\beta) \) accounts for this phenomenon. At the top most location, the fluid sinks down because of gravity. When the liquid moves down, it exchanges heat with secondary. The hot leg, heater, cooler, cold leg are analyzed with the following energy conservation equation.

\[
\frac{\partial T}{\partial t} + \frac{W}{A p_0} \frac{\partial T}{\partial s} - a \frac{\partial ^2 T}{\partial s^2} = \begin{cases} \frac{q_s}{A p_0 c_p} - \frac{u_a c_s (T - T_{mcl})}{A p_0 c_p} & \text{Source} \\ \frac{u_h c_s (T - T_{mcl})}{A p_0 c_p} - \frac{u_s c_s (T - T_{mcl})}{A p_0 c_p} & \text{Hotleg} \\ \frac{u_s c_s (T - T_m)}{A p_0 c_p} + \frac{u_s c_s (T - T_{mcl})}{A p_0 c_p} & \text{Sink} \\ \frac{u_l c_s (T - T_{mcl})}{A p_0 c_p} & \text{Cold leg} \end{cases}
\]  

(16)

Fig. 39: The Design for THTD-1.

Fig. 39: A) Front View for Cross-Over Junction.

Fig. 39: B) Top View for Cross-Over Junction.

where, \( \zeta_{sl} = \pi d_{sl}; \zeta_l = \pi D_l; \zeta_o = \pi d_o; \zeta_i = \pi d_i; \zeta_{scl} = \pi d_{scl} \). Here, the average liquid temperatures of the cold leg & average liquid temperature in the cooler primary side, mean hot leg liquid temperature and mean water temperature in heater section are respectively denoted by \( T_{mcl}, T_{mc}, T_{ml}, T_{mh} \).

Also, the overall heat transfer coefficients based on the inside wall of the sink, cold leg inside walls and hot leg inside walls, cold leg outside, hot leg outside walls are respectively given by \( U_{wci}, U_i, U_o, U_{hi}, U_{ho} \). As the inner wall has been made of an insulating material, the radial heat transfer conduction is negligible. For the steady state, the Eq.16 is modified as described below,

\[
\frac{W}{A p_0} \frac{\partial T}{\partial s} - a \frac{\partial ^2 T}{\partial s^2} =
\]
\[
\begin{aligned}
\rho_0 \frac{\partial T}{\partial t} &= \frac{W}{A} + \frac{\partial^2 T}{\partial s^2} \\
&= \begin{cases}
\frac{q_{b,i}(T - T_{mcl})}{A \rho_0 C_p} & \text{Source} \\
\frac{u_{hi,sh}(T - T_{mcl})}{A \rho_0 C_p} & \text{Hot leg} \\
\frac{U_m(T - T_{mcl}) + u_{ho,sh}(T_{mcl} - T)}{A \rho_0 C_p} & \text{Sink} \\
\frac{U_i(T_{mcl} - T)}{A \rho_0 C_p} & \text{cold leg}
\end{cases}
\end{aligned}
\]

\[17\]

9.2.2. Analysis for THTD-II

The Fig. 40 illustrates the design for THTD-II. Due to heating action, the lower density fluid moves upward towards the heat sink section. In this design, there is no sand-witched crossover device.

\[18\]

In the mathematical model used for analysis, same conservation of mass and momentum equations are applicable for THTD-2. The energy conservation equation for the THTD-2 is modified as described below,

\[19\]

It has been observed that the flow rate for fluid (heat transport capability) for THTD-II is lower than that of THTD-I. In THTD-I, the flow rate is higher because fluid does not exchange heat, when fluid rises above. The THTD-II has no cross-over device. In THTD-II,
when the cooling length is higher than buoyancy driven pressure head, the device II can fail to perform its functioning. The highest temperature in THTD-II is higher than that of THTD-I, because of higher heat transport capability by THTD-I, (Fig. 41).

![Graph showing temperature distribution](image)

**Fig. 41:** Comparison of Overall Temperature Distribution.

In Fig. 42, the consequence for change in outer diameter has been investigated, keeping the height of loop constant & the heater power fixed at 1500W. As the diameter increased, because of reduction in frictional loss, the flow rate is increased.

![Graph showing flow rate vs diameter change](image)

**Fig. 42:** Change in Diameter vs. Flow-rate.

Bending losses are taken from the handbook of hydraulic resistances [25]. The Code for Thermalhydraulic Analysis (COTA) has been used for modeling and development of THTDs. The developed R code is used to compare the performance of THTD I and THTD II. Physically, the outer diameter of THTDs fits into the central region of annular fuel, thus THTDs function as a moderating device (Fig. 18.B).

### 9.3. Monitoring the radioactivity levels

Monitoring the radiation level surrounding the nuclear reactor is one of the important tasks from reactor operators’ health point of view during the reactor operation. Saxena et al. have developed ISMRAN detector for the detection of reactor antineutrinos during start-up, shutdown and steady state operations [26]. This detector also helps in determining the power and reactivity (Fig. 43).

![Radiation Monitoring System](image)

**Fig. 43:** Radiation Monitoring System.

Inside this instrument, electron antineutrino reaction with proton takes place with very small interaction cross-section \(6 \times 10^{-43} \text{ cm}^2\) as given below,

\[
\bar{\nu}_e + p \rightarrow e^+ + n.
\]  

(20)
The produced positron, having almost all of the energy as that of the incoming neutrino, loses energy in the detector volume through ionization as well as annihilation with an electron which in turn produces two rays of 0.511 MeV. The event by the positron and the resulting γ-rays provide output signal from this device.

9.4. Automation for safer operation

For the stable reactor operation, various plant parameters are required therefore software is developed to monitor various parameters. The software provides interactive graphical user interface and allows monitoring of various parameters during the normal and off-normal transients (Fig. 44).

In order to ensure the maintenance and operational safety, the online supervision of plant status is one of the most important tasks. Conventionally, the fault threshold levels for each plant parameter are preset and an alarm signal is generated as soon as the observed signal shows the anomaly. However, in many cases, when an anomaly is observed, it may be too developed to undo. Therefore, a model-based method has been used, which is better for early fault detection than the conventional threshold level-based systems. For a layman operator having no knowledge about plant dynamics, the automation is required and therefore it is embedded in the plant management software.

In the past, several cases are experienced in various labs hacking vital information and procedures which are attempted by external agencies. In order to prevent any type of external threat and data hacking, the computer rooms are protected with secured network systems to prevent cyber-attacks by external agencies.

![Fig. 44: Autonomous Overall Plant Management.](image)

On October 25, 2018, Unit-1 of Kaiga Generating Station (KGS-1) completed 895 days of uninterrupted operation. This has established the world record of long continuous operation among all the Pressurized Heavy Water Reactors (PHWR).

This Pressurized Heavy Water Reactor (PHWR) unit has been operated since May 13, 2016. On October 25, 2018, this achievement for KGS-1 stands first among all PHWRs and second among all nuclear power reactors in the world (of all technologies) in terms of uninterrupted reactor operation. Without being shut down, both AGRs and PHWRs are designed to be refueled.

Interestingly, on Dec. 10, 2018, the PHWR at Kaiga has established world record of continuous operation for 941 days, at a Plant Load Factor of about 99.3% without any incident (941 days from May 13, 2016 to Dec. 10, 2018). Earlier, the record of uninterrupted reactor operation was held by Unit 2 of the Heysham power plant. This reactor was operated from February 18, 2014 to September 15, 2016 for 940 days.

10. Recycling of the spent fuel

The first Indian fast breeder reactor achieved criticality and started operation when there were no computers available to use and other nations were not reliable for co-operation (Fig. 45). This reactor has been running successfully without single technical failure since the past several decades. It makes use of sodium bonded metallic fuel pins. Nuclear fuels with BISO and TRISO coated particles developed at BARC have also been irradiated in this reactor. The fast breeder test reactor (FBTR) is resilient to various external events as enlisted below. The technology is used to reduce plutonium build-up converting Thorium into Uranium (U²³³) for third stage reactors.

![Resilience of FBTR to external events –](image)

- Earthquake
- Flood
- Cyclone
- Power Failure
- Lightning
- Geotechnical
- Chemical Explosion
- Meteorology
- Hydrology

![Fig. 45: Early Prototype Fast Reactor (Also Known As FBTR) Where BISO and TRISO Particle Fuels Are Irradiated.](image)
Irradiation of TRISO particles is accomplished within a high temperature environment of the sodium-cooled fast reactor. The annular fuels described earlier are utilized for fast reactors. The discharge of Sodium though the piping is demonstrated in Fig. 46. Through the decades of operational experience gained, a new sodium cooled reactor (GEN IV Prototype Fast Breeder Reactor) has been built-up at Kalpakkam, India (Fig. 46 and Fig. 47) [27,28].

The plutonium recovered from the burned fuel after reprocessing has been used to manufacture the fresh fuel along with Thorium at Nuclear Fuel Complex. This fresh fuel will be used as input for the 3rd stage of the Indian Nuclear Power Program.

Moreover, the developed fast reactor can bum different actinides reducing the nuclear waste drastically to a lower level, hence it supports not only for non-proliferation but also for radioactive waste management. The U$_{233}$ obtained from Th$_{232}$ surrounding the FBR fuel, is used as input fuel for Advance Heavy Water Reactors (AHWRs) to be started in the third stage of Indian three stage nuclear power program. Without usage of U$_{233}$ and Pu$_{239}$, AHWRs (or third stage reactors) cannot attain the criticality and start up. The AHWR criticality layout is shown in Fig. 48.

The radioactive decay chain of Th$_{232}$ is delineated in Fig.49.
The buildup of $^{233}U$ when Thorium is irradiated along with Pu in the AHWR from the third stage of the nuclear power program has been shown in the Fig. 50 as a function of fluence. The AHWR produces very small quantities of plutonium as there is no $^{238}U$ in the fuel. Better proliferation resistance of Advance Heavy Water reactor (Plutonium 10% lower in spent fuel than in a PWR) has been proved by the scientists from Brookhaven National Lab [29]. The innovative fuels developed at BARC further improve the proliferation resistance of reactors for Three-stage Nuclear Power Program.

The Fig. 51 overviews and explains Three-stage Nuclear Power Program to utilize nuclear energy. These stages are connected with each other utilizing the nuclear waste.

Parallel to AHWRs, GEN IV reactors including IHTR, IMSBR, etc. have been developed at BARC to utilize thorium fuel in the third stage of Indian Nuclear Power Program (see the Table 4). The Pu inventory is burned in the third stage, in order to achieve criticality and establish equilibrium fuel cycles for $^{233}U$ reactors. The first, second and third stages are expected to generate 12GW, 300GW and 500GW of power respectively, including process heat energy in each stage. As the third stage will generate 500GW of power (more than second stage), large amount of Pu inventory are required for sustained operation of third stage reactors. Thus, the developed safer nuclear fuels enable continuous desirable Hydrogen production on the secondary side of the intermediate heat exchanger through various low temperature Hydrogen production cycles. Nonetheless, the fuels in the form of BISO/TRISO particles and multilayered fuels which are capable of withstanding in high neutron fluence and temperature environment, enable Hydrogen production through high temperature cycles e.g. Sulfur-Iodine (S-I) cycle.
<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Indian Innovative reactors&lt;sup&gt;9&lt;/sup&gt;</th>
<th>Nuclear Fuels used&lt;sup&gt;10&lt;/sup&gt;</th>
<th>Stage</th>
<th>Generations in reactor technology</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>Apsara</td>
<td>U&lt;sup&gt;233&lt;/sup&gt; Al alloy</td>
<td>I</td>
<td>Generation I</td>
</tr>
<tr>
<td>2</td>
<td>Cirus</td>
<td>Natural Uranium</td>
<td>I</td>
<td>Generation I</td>
</tr>
<tr>
<td>3</td>
<td>Dhruva</td>
<td>Natural Uranium</td>
<td>I</td>
<td>Generation I</td>
</tr>
<tr>
<td>4</td>
<td>Zerlina</td>
<td>Natural Uranium</td>
<td>I</td>
<td>Generation I</td>
</tr>
<tr>
<td>5</td>
<td>Pressurized Water Reactor</td>
<td>Shortage of U&lt;sup&gt;235&lt;/sup&gt;, so not prioritized</td>
<td>I</td>
<td>Generation III+</td>
</tr>
<tr>
<td>6</td>
<td>Pressurized Heavy Water Reactor</td>
<td>Uranium oxide</td>
<td>I</td>
<td>Generation III+</td>
</tr>
<tr>
<td>7</td>
<td>Fast Breeder Test Reactor (Early Prototype Fast Reactor )</td>
<td>*Plutonium-Uranium mixed carbide fuel *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;) TRISO coated particles * Thorium dioxide</td>
<td>II</td>
<td>Generation I</td>
</tr>
<tr>
<td>8</td>
<td>Paurnima I</td>
<td>Plutonium Oxide</td>
<td>II</td>
<td>Generation I</td>
</tr>
<tr>
<td>9</td>
<td>Prototype Fast Breeder Reactor</td>
<td>*Mainly Pu&lt;sup&gt;239&lt;/sup&gt; *Plutonium-Uranium mixed carbide fuel *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;) Multi-layered fuel * Thorium dioxide</td>
<td>II</td>
<td>Generation IV</td>
</tr>
<tr>
<td>10</td>
<td>Innovative Accelerator Driven System</td>
<td>*Spent fuels along with Thorium</td>
<td>II</td>
<td>Generation IV</td>
</tr>
<tr>
<td>11</td>
<td>Innovative Gas Cooled Fast Reactor</td>
<td>*Mainly Pu&lt;sup&gt;239&lt;/sup&gt; *Plutonium-Uranium mixed carbide fuel *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;)Multi-layered fuel *Thorium dioxide</td>
<td>II</td>
<td>Generation IV</td>
</tr>
<tr>
<td>12</td>
<td>Innovative Lead Cooled Fast Reactor</td>
<td>*Mainly Pu&lt;sup&gt;239&lt;/sup&gt; *Plutonium-Uranium mixed carbide fuel *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;)Multi-layered fuel *Thorium dioxide</td>
<td>II</td>
<td>Generation IV</td>
</tr>
<tr>
<td>13</td>
<td>Innovative Fast Reactor</td>
<td>*Mainly Pu&lt;sup&gt;239&lt;/sup&gt; *Plutonium-Uranium mixed carbide fuel *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;)Multi-layered fuel *Thorium dioxide</td>
<td>II</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>Candle type reactor</td>
<td>*Mainly Pu&lt;sup&gt;239&lt;/sup&gt; *Plutonium-Uranium mixed carbide fuel *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;)Multi-layered fuel *Thorium dioxide</td>
<td>II</td>
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<tr>
<td>15</td>
<td>Kamini</td>
<td>U&lt;sup&gt;233&lt;/sup&gt; Al alloy</td>
<td>III</td>
<td>Generation I</td>
</tr>
<tr>
<td>16</td>
<td>Paurnima II</td>
<td>U&lt;sup&gt;233&lt;/sup&gt; with (Pu&lt;sup&gt;239&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>III</td>
<td>Generation I</td>
</tr>
<tr>
<td>17</td>
<td>Paurnima III</td>
<td>U&lt;sup&gt;233&lt;/sup&gt; Al alloy with (Pu&lt;sup&gt;239&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>III</td>
<td>Generation I</td>
</tr>
<tr>
<td>18</td>
<td>Advance Heavy Water Reactor</td>
<td>*(U&lt;sup&gt;233&lt;/sup&gt;–Th) O&lt;sub&gt;2&lt;/sub&gt; &amp; (Pu&lt;sup&gt;239&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>III</td>
<td>Generation I</td>
</tr>
<tr>
<td>19</td>
<td>Innovative High Temperature Reactor (IHTR-A, IHTR-B, IHTR-C)</td>
<td>*(U&lt;sup&gt;233&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt; &amp; (Pu&lt;sup&gt;239&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt; *( UC&lt;sub&gt;2&lt;/sub&gt;&amp; ThC&lt;sub&gt;2&lt;/sub&gt;) Multi-layered fuel</td>
<td>III</td>
<td>Generation IV</td>
</tr>
<tr>
<td>20</td>
<td>Innovative Molten Salt Breeder Reactor</td>
<td>*Uranium-233&amp;Thorium * Molten Fluorides of Uranium and Thorium</td>
<td>III</td>
<td>Generation IV</td>
</tr>
<tr>
<td>21</td>
<td>Innovative Supercritical-Water Reactor</td>
<td>*(U&lt;sup&gt;233&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt; &amp; (Pu&lt;sup&gt;239&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt; * Fuels in Carbine form</td>
<td>III</td>
<td>Generation IV</td>
</tr>
<tr>
<td>22</td>
<td>Innovative Thermal Reactor</td>
<td>*(U&lt;sup&gt;233&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt; &amp; (Pu&lt;sup&gt;239&lt;/sup&gt;–Th)O&lt;sub&gt;2&lt;/sub&gt; * Fuels in Carbine form</td>
<td>III</td>
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</tbody>
</table>

<sup>9</sup>These energy production systems are scalable from 1 MWe to 1500 MWe as per the demand. <sup>10</sup>Nuclear fuels in nitrides form having better thermal conductivity are also developed for these reactors.

11. Some of peaceful applications from Nuclear energy

Nuclear fuels are clean, high energy density fuels. Nuclear fuels allow development of following environmentally benign applications.
11.1. Process heat supply for extraction of bitumen from oil sands

Oil sands, also known as bituminous sands, are highly viscous semi-solid form of heavy oil, thus difficult to pump up on the surface. Following methods are used to extract the bitumen:
1) Combustion Overhead Gravity Drainage
2) Steam Assisted Gravity Drainage
3) Vapor Extraction
4) Toe to Heel Air Injection
5) Cold Heavy Oil Production with Sand
6) Surface Mining
7) Cyclic Steam Stimulation

The process heat required in these methods is supplied from nuclear reactor. The high temperature and high pressure tertiary fluid is used to extract the bitumen. The Fig. 52 explains the method to couple the nuclear reactor with an oil sand extraction plant.


The high temperature, high pressure secondary fluid is divided into two parts and utilized as follows:
i) The part of process heat supplied to turbines is used to generate the electricity for entire plant
ii) The remaining part of process heat is used to heat up the tertiary fluid to the temperatures and pressures required extract the product.

The fluid containing bitumen is processed and sent to the central processing unit where Hydrogen is selectively separated from the mixture using membrane with special nano-materials.

11.2. Some of the applications of secondary Hydrogen energy source

If controlled, the nuclear based continuous mass production of hydrogen with higher efficiency offers several advantages including lower cost of production.

As the secondary fuel Hydrogen has very high heat of combustion (286 kJ/mol) with byproduct water; the Hydrogen has very high demand. The clean Hydrogen fuel allows to develop its own several environmentally benign applications.
In rocket science, the Hydrogen fuel has been used by ISRO to launch hundreds of satellites including Mars orbiter (Fig.53). Compared to earth storable liquid and solid propellants, Hydrogen and Oxygen generate much higher thrust with the indigenous rocket engine. The indigenously developed rocket engines with propellants at low temperatures have higher payload capacity.

![Image of Glorious Accomplishment of Launching Mars Orbiter Payload with Hydrogen Fuel in Single Attempt.]

Some of the products developed at BARC utilizing Hydrogen fuel are described below.

In Fig.54, the product makes use of the Hydrogen, to run the stationary electric generator for back-up power in emergencies. Inside the generator, Hydrogen and oxygen react with each other with a byproduct of water (Fig. 54). A system with similar dimensions is used in the Hydrogen based battery replacement centre (Fig. 55).

![Image of (Stationary) Hydrogen Fuelled Generator for Back-Up Power in Emergency.]
Another Hydrogen based product is a mobile plant with Hydrogen fuel. This mobile plant can supply additional Hydrogen stored to other Hydrogen operated vehicles (Fig.56). Moreover, this plant utilizes Hydrogen as one of the reactants for fuel cells stacked inside. Since the output voltage of the fuel cell is small (<1V in realistic operating conditions), fuel cells are stacked together in series inside the Hydrogen based charging centre. This method allows replacement of the discharged batteries from battery-operated vehicles (Fig. 56). As this plant is mobile, the underground piping cost to carry the Hydrogen gas is eliminated, thus the refueling operation of Hydrogen fuel is simplified with enhanced safety. The Fig. 55 shows Hydrogen based mobile power plant for the supply of Hydrogen fuel as well as batteries. In the cities situated near the seashore, to avoid traffic jams, the electric boats are an alternative option to commute. Ro-Ro boats are run with Hydrogen from the mobile plant (Fig. 55).

Additionally, the Hydrogen propelled automated submarine has been developed indigenously at BARC to perform search operations deep under the sea (see Fig. 57). The submarine is fitted with a trans-receiver which sends and receives commands from satellite about the current location of the submarine. Using the sensors placed in the submarine, the location of unknown object to be searched deep inside the ocean can be found out. As the Hydrogen energy density is approximately three times more that of Diesel, higher thrust and speed is achieved by the Hydrogen fuelled submarine. Hydrogen fuelled submarine is faster and useful for deeper search operations (Fig. 57) under the sea.

**11.3. Dedicated transmission lines for electric locomotives**

India has one of the largest railway networks in the world. In order to provide electric supply for electric locomotives with 24 hours of availability, separate dedicated grids are being constructed running from nuclear reactors. Autotransformer based electric transmission lines are used to supply 25 kV power to the trains, however, some lines transmit power at 50 kV to reduce energy losses (Fig.58).

In order to protect the environment against pollution, Hydrogen fuel trains are used. The Hydrogen trains totally eliminate the high installation cost of overhead wires; therefore Hydrogen trains are likely to be an economical alternative for electric or diesel engine trains. The Fig. 59 shows Hydrogen fuelled Palace on Wheels train. As the frictional coefficient is not constant from time to time, linear state space model fails for speed control of Hydrogen fuelled train. The Fig. 60, 61, 62 represent results for velocity control, normalized flow-rate and normalized breaking input for Hydrogen fuelled train using non-linear control.
11.4. Hydrogen fuelled civilian aircrafts

From the experience of a single seated Solar Impulse-2, which revolved around the world with 12 stops, it can be vividly concluded that the lower solar energy density is not sufficient to fly an aircraft. The usage of biodiesel against petroleum reduces Carbon monoxide and Sulfur contents, thus presently being used. Hydrogen is cleaner fuel than biodiesel fuel. As the volumetric energy density of methane gas is more than that of hydrogen gas by a factor of 3.2, large quantity of Hydrogen fuel is required. Private firm in India has developed aircraft that utilizes environmentally benign Hydrogen fuel (Fig.63).

Due to higher energy density of Hydrogen than Solar energy, the planes fuelled with Hydrogen have capacity to carry larger number of passengers and goods with more weight. Similarly, larger capacity Hydrogen fuelled aircrafts are developed by CSIR lab (Fig.64).

11.5. Recycling of waste plastic

By recycling the waste plastic, fuels in the form of Hydrocarbons with lesser sulfur contents have been produced for domestic as well as industrial applications by Nasik (Maharashtra) Municipal Corporation (Fig. 65). The energy required to convert plastic waste into Hydrocarbons is supplied from nuclear reactor. By operating this plant with the help of a nuclear power plant, twenty four hours of continuous operation is possible which enables recycling of tons of waste plastic per 24 hours.
11.6. Pollution free Iron ore processing

The Innovative High Temperature Reactor can raise the coolant temperature up to 1000°C. The processing of iron ore with the energy obtained from IHX secondary side eliminates the necessity of burning of coals, thus CO₂ emissions into the environment get avoided. A prototype high temperature system developed at BARC has been handed over to a private steel production firm.

11.7. Gamma radiation processing plant

Apart from energy generation required to run machines, efforts have been made for the preservation and disinfection of the food items consumed by humans or animals. The hot and humid climate environment is suitable for the growth of numerous insects and microorganisms that can destroy stored crops and cause spoilage of food easily (Fig.66). The possibility of spoilage of the food is also due to chemical and physiological changes in stored foods. When potatoes sprout, contents of glycoalkaloid compounds also start to rise. When potatoes with excessive glycoalkaloid compounds are eaten, become poisonous. When a person consumes glycoalkaloid compounds in larger amounts, the consumption can cause fever, headaches, and sometimes, even death. Similarly, other food products turn poisonous when not stored properly.

BARC is focusing on radiation processing along with several other methods so that food items can be preserved for longer durations without spoilage. All these processes are accomplished inside the Gamma Radiation Processing Plant (Fig.67).

11.8. Desalination plants for drinkable water

Every year, over 75% children & 40 million people are affected by water borne diseases. About 12% of the Indian populations are anticipated to have urinary stones; among them, 50% possibly end up with loss of kidney functions [31].Shortage of water is another problem for growing population due to unreliability of rain. Because of fluoride contamination in water, children below 14 years of age (nearly six million) suffer from fluorosis. In the country, bacteriological contamination, which leads to diseases like diarrhea, cholera, hepatitis etc., is at risk level. In the ground water of the country, arsenic is also a hazardous contaminant risking more than 10 million people. Salinity and hardness in water contamination due to Iron are other major concerns. These problems are mitigated with desalination of seawater technology available.

The desalination is a process of removing salts from the water, making it suitable for human consumption (Fig.68).It is possible to operate the desalination plant on the process heat from the nuclear reactor. A method has been developed to connect the desalination plant with Innovative High Temperature Reactor (IHTR) to utilize the process heat generated by IHTR at BARC.
An alternative method has been established and developed at BARC which utilizes Multi-Effect Distillation using Thermo Vapour Compressor effectively called as MED-TVC for the production of low conductivity distilled quality water by using low or medium pressure steam and electricity. The desalinated water with lesser salts from the desalination plant built at BARC is used for watering the trees.

11.9. Medical applications developed from spent fuel

The radioisotopes from the spent fuel of the first stage are utilized for nuclear medicines and other environmentally benign applications. Out of many applications, for brevity, here the application of Ru106 plaque in brachytherapy is explained. Ru bearing Sealed Source is used for Eye Cancer Treatment Applications. Prithwish Sinharoy et al have patented Ru106 bearing sealed source [32]. This Ru based plaque source is developed, right from the separation of the fissiongenic radionuclide from High Level Waste (HLW) followed by its immobilization onto the silver substrate and eventually encapsulated into silver plaque indigenously. Thus, the availability of Ru106 greatly help in reducing the cost of brachytherapy and saving vision. Utmost care is required while using radio-isotopes for medical applications. The stable and safe chemical compositions of Iodine, Zinc, etc. from the spent fuel along with other medications are used to cure Corona in the hospital at BARC. Stabilized form of Sodium, from the intermediate loop of sodium fast reactor is used for the preparation of the sanitizers in Indira Gandhi Centre for Atomic Research. Additionally, some of the stable and safe chemical elements from the spent fuels are used for the development of the fertilizers for the plants.

12. Nuclear security

It is a well known fact that each matter in the world is composed of atoms with its constituents. Each atom has a nucleus with one or more electrons in its orbits around the nucleus. Therefore, Nuclear Security has a very broad spectrum. Nuclear security is the detection and prevention of, and response to unauthorized access, unauthorized establishment without permissions, illicit transfer or other malicious acts involving radiological or hazardous material or their associated facilities. However, nuclear security is different from nuclear safety, which involves prevention, mitigation of and protection against mishaps involving nuclear material or related facilities that could give further rise to radiation hazards.

In India, the Atomic Energy Regulatory Board reviews the nuclear security within the boundary of a nuclear facility which is integrated with the technical design of the facility. India has devised a Design Basis Threat document for protection at its facilities. The national Design Basis Threat takes into account the existing threat from saboteurs, terrorists, thieves, malicious actors, their characteristic capabilities as well as possibility of the threats. An independent regulatory body from AERB regularly audits physical protection systems. In the daily practice of nuclear security, India’s national systems of Nuclear Material Accounting & Control (NUMAC) along with personnel reliability measures play a vital role.

12.1. Technological advancement

Two technological dimension aspects for nuclear security in India have been investigated. The first one is the design and deployment of secure radiation detectors, portals, secure communication networks, real-time tracking systems, Radio Frequency ID cards, sensors, infrared cameras and other barriers with similar technologies. These supportive technologies are developed indigenously. The second technological dimension includes the development of procedures for nuclear fuel cycle technologies with proliferation resistant nuclear fuel technology which lower the risk of a security breach and nuclear proliferation. India has developed fuel cycles with Thorium & Plutonium that obviate both the buildup of stockpiles as well as the necessity to store large amounts of spent fuel in underground repositories containing U233, U235, Pu239 which could be easily accessed by malefactors in the future.

Indian scientists have designed proliferation resistant reactors e.g. Advanced Heavy Water Reactor (AHWR) along with other reactors using Thorium and Plutonium, which also produce high energy gamma-emitter U232 (as a by-product), that makes use and access for the spent fuel by unauthorized entity difficult. Moreover, the technologies for vitrification of radioactive waste have been developed which have the benefit of making access to waste by terrorists intending to fabricate a radiological device, difficult. The vitrification process has been used to convert recycled-outdated-decayed sources from equipments in the glassy solid form. Thus, India has achieved an impeccable record on nuclear non-proliferation.

12.2. Global Centre for Nuclear Energy Partnership for the growth of the peace

In order to develop international co-operation for peaceful usage of nuclear energy, the Global Centre for Nuclear Energy Partnership (GCNEP) has been established by India. Having India already advanced nuclear engineering technologies, GCNEP also educates and encourages foreigners for the usage of nuclear energy (Fig.69).
As English is the official language of India, GCNEP organizes and imparts the following advances in English to foreigners

1) School of Advanced Nuclear Energy System Studies (SANESS)
2) School on Radiological Safety Studies (SRSS)
3) School of Nuclear Security Studies (SNSS)
4) School for Studies on Applications of Radioisotopes and Radiation Technologies (SSARRT).
5) School of Nuclear Material Characterization Studies (SNMCS).
6) School of Architecture, Design and Marble Carving Technology (SADMC)

Satellites launched by ISRO (104 in a single launch) for several countries have been keeping watch on all over the world and extraterrestrial activities.

12.3. Nuclear Weapons Types

Since every atom has a nucleus, nuclear security has a broad spectrum. The nuclear security is concerned with chemical weapons, nuclear weapons, biological and computer viruses. Many countries have been arguing that the Nonproliferation Treaty (NPT) is just a plot to maintain the dominance of those who already had nuclear weapons before 1\textsuperscript{st} January 1967. Meanwhile, the focus of Indian scientists was never on the negative development of nuclear energy. However, NPT signatories including America, China have been developing and proliferating deadly biological viruses (Corona, SARS, MERS, Ebola), chemical and nuclear weapons all over the world, killing hundreds of thousands of innocent people causing NPT as a blunder game. The containment of any hazardous activity is the most important safety criteria that must be satisfied by every country. Thus, countries which have invented and first time used biological, nuclear, chemical weapons must be forbidden. Recently, second wave of the Corona epidemic has been spreading from China, US and UK.

Terrorism with series of blasts at Railway stations, attacks at various renowned university campuses, renounced International Hotels inside India, breaching the peace, through the agents like Ajmal Kasab have reflected various terrorist organizations, such as LeT, JeM, Al-Qaeda, ISIS, etc. Just attacks at the Hotel Taj Mahal Palace (owned by the TATA group) killed at-least 170 people including many foreigners. Therefore, Dr. Manmohan Singh hosted a meeting of Sherpas for the Nuclear Security Summit (NSS) in New Delhi in 2012. In these Sherpa meetings, the participants from more than 170 countries and four international organizations have also participated and thereby decided the work plans for Nuclear Security. The Sherpas or representatives of the governments have united at Delhi against nuclear terrorism initiated and operated by ISIS or Chinese militants network, which has affected adversely globally. Some of the measures taken include lowering the usage of Highly Enriched Uranium (HEU) and Plutonium against to the TRIGA reactor having 70\% to 93\% enrichment. Also, preventing the illegal trafficking of nuclear materials, viruses from source countries such as China had been emphasized, during the meeting. All the participating Sherpas from more than 170+ countries have agreed for the necessity to combat against Nuclear Terrorism. India has been co-operating proactively with the Interpol’s Radiological and Nuclear Terrorism Prevention Unit and the World Customs Anti-Chinese Organization with the co-operation of Defense Secretary of India. The nations following or assisting China’s nuclear program must be debarred.

Clandestine dangerous scientific activities, illogical religious principles, attacks on common people, transfer of nuclear weapons to the neighbor by China have devastated the lives of millions of ordinary and innocent people all over the world. Dangerous countries are producing and spreading hazardous nuclear materials e.g. Coronavirus, adversely affecting ordinary and innocent people of the country.

The digital instruments developed by the department of metrology in India ensure that reactors will be loaded with the required amount of the fissile inventory. India’s nuclear technological advancements including Three-stage Nuclear Power Program eliminate the loopholes from the NPT. India has recently contributed one million USD to the Nuclear Security Fund (NSF) of IAEA. India has contributed at IAEA economically, as well as through knowledge with several decades of reactor operations experience.
Nations contributing with other nations either economically or technically for the development of biological, nuclear or chemical weapons breaching the peace in India have been mainly responsible for proliferation. Dangerous countries producing various types of venomous nuclear materials have targeted and victimized millions of common and innocent people of the India, hence the Indian navy, military and air force are declared as autonomous bodies with privilege. Their main campus is established in Chennai. India is a well-known leading party to the global initiative to combat against nuclear terrorism and has pioneered technological advancements for nuclear detection, forensics, and response.

After the Fukushima Daiichi nuclear reactor disaster, AERB in India has tightened safety criteria rigorously, some of which are briefly described in this paper. The civil nuclear energy sites have been the principal attraction of targets by terrorists. Attacks with plane on reactor building, causing large release of radioactivity through the disaster to produce significant civilian casualties and land contamination are the main motives of the terrorist groups. In order to provide the highest level of safety against terrorist identified zones (operated by LeT, JeM, ISIS, Al-Qaeda, etc.), computerized 3D carving method has been developed which can carve out containments and other civil structures from specialized stones for newer reactors. The reactor structural are so strong that they remain intact even during accident scenario with airplane crash. The redundancy of components, on-site availability of spare parts, lead to the mean down time (MDT) of 4h, that is, 4,566 × 10⁻⁴ y and mean time between failures (MTBF) of 37.7 y, thus the availability becomes, A = \frac{1}{(1+\text{MTBF})} = 99.9987\%, setting a world record for excellence in continuous reactor operation!

13. Conclusion

Different reactor accidents at Chernobyl, TMI-2, Fukushima Daiichi, etc. have been analyzed. From outcomes of these studies, remedy nuclear fuels have been developed at Nuclear Fuel Complex, Hyderabad. The developed nuclear fuels have negative temperature coefficient and larger heat transfer area. These fuels withstand without failure in different accident scenarios due to its relatively low operating temperature in the reactor cores. All the developed systems either use process heat or electricity generated by nuclear fuels; reducing CO₂ etc. emissions into the environment caused by conventional sources of energy.

The indigenously developed BISO and TRISO fuels at BARC have been irradiated and tested in the second stage of fast breeder reactor. Developed fuels withstand extreme temperatures and pressures conditions of reactor core hence cannot be melted in any postulated accident. All the developed fuels have been utilized for Indian GEN IV reactors. The developed safer nuclear fuels and reactor technology allow safe and safer co-generation of Electricity and Hydrogen for mobile power plants; eventually taking care of the environment. The process heat available across the reactor core has been utilized. Moreover, several medical applications (including that for brachytherapy) have been developed with radioisotopes from spent fuel. The safely produced Hydrogen gas has been utilized in many ways. The Indian technological advancement utilizing the proliferation resistant Thorium fuel is the solution to the proliferation issue. India’s three-stage nuclear power program consisting of innovative GEN-IV reactors which utilize the Thorium fuels along with several H₂ applications assist for non proliferation. The recycling method is very important for energy deficient India.

India has invented and imparted world, the processes to achieve the peace through e.g. 3-Stage Nuclear Power Program with several peaceful applications however, countries, such as China, Syria, America etc. have been disturbing the peace by producing various types of hazardous nuclear materials and proliferating them. This has caused nuisance and devastation of crores of ordinary, innocent people in the country. In the history, cyber attacks with viruses and illegal access of Indian scientific documents without acknowledgement by China, America etc have been experienced in various places in India.

The countries which are not using illustrated techniques including three-stage Indian nuclear program are dangerous in terms of proliferation hence responsible for proliferation of hazardous nuclear materials. As illustrated, India’s nuclear policy with Three-stage Nuclear Power Program eliminates the loopholes of the NPT.

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Compact High Temperature Reactor, Reactor Technology & Engineering, BARC Highlights.


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