Nuclear Power Generation and Challenges

Dr. S.R. Awasthi
Former GM, BHEL, Former Director (Research), RNTU, Bhopal (M.P.) India.

ABSTRACT
In view of the seriousness of climate change issue, it has become necessary to do away with the fossil fuel based power generation in power sector in a phased manner which cater for base load. Alternatively nuclear power plants can take this responsibility. However, they are fission based which has some problems, mainly safety aspects, radiation hazards, disposal of spent nuclear waste. This paper discusses these issues and also the futuristic fusion reaction based, nuclear power which is much safer process of using nuclear energy.

Keywords: Nuclear power, nuclear reactors, nuclear fission and fusion

I INTRODUCTION

Acharya Kanada, also known as Kashyapa, an ancient Indian natural scientist and philosopher is the father of atomic theory. He formulated the theory of atoms hundreds of years before Christ (B.C.).

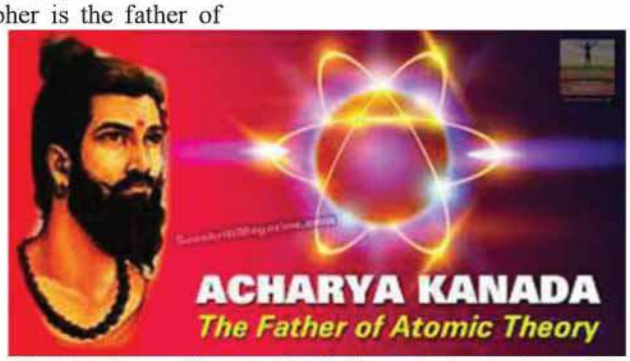

Fig. 1 Acharya Kanad, the Father of atomic theory [1]

There are two processes of nuclear reaction during which huge amount of energy, held in the nucleus (core), is released in the form of heat. In fission reaction, a heavy and unstable nucleus is split into two or three lighter nuclei. The fusion is the reverse of fission in which two lighter nuclei combine together.

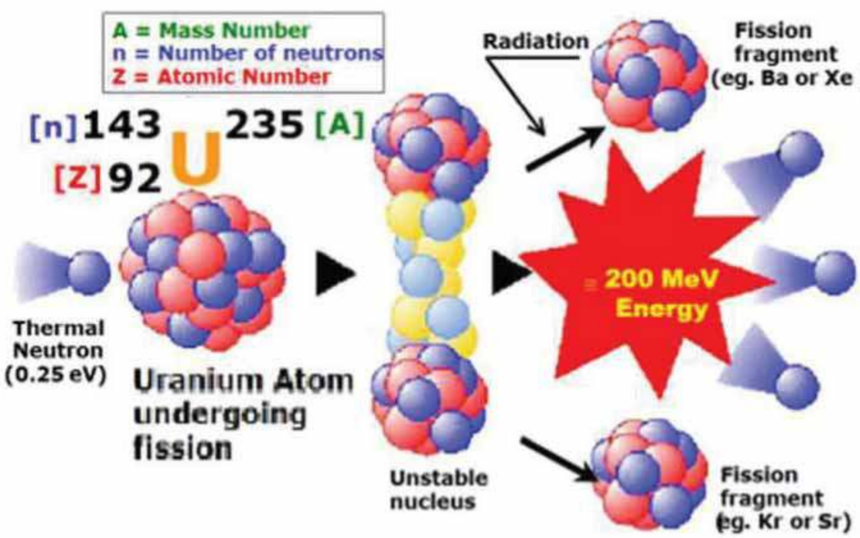

Fig. 2 Nuclear fission of Uranium-235 [2]

This paper discusses the working of fission reactors and associated issues related to safety and the worst nuclear disasters that have taken place around the globe. The fusion reactor is at the R&D stage and its working and status are also explained.

In a coal based thermal power plants, the coal is burnt in the a boiler and the heat produced is used to convert water into the steam whereas, in a nuclear power plant, a nuclear reactor is used in which heat is produced by fission process and heat is released which is used to convert water into steam.

In View of the above, only the Nuclear Reactors are explained in this paper as the Turbine, Generator, Excitation System, Controls, Protections, Transformers Etc. are Similar to Thermal Power Plants which are already discussed by the Author in March 2021 (Vol. X, Issue XX) of the Research Journal 'Anusandhan'.

There are different types of nuclear reactors. However, the working principles for using nuclear power to produce electricity are the same for most types of reactors.

Presently, the share of electricity from nuclear power reactors in the submarines and large naval ships is about 85% of the world's total nuclear electricity.

II FISSION REACTORS: WORKING AND ISSUES

A nuclear reactor produces and controls the release of energy from splitting the atoms. In a nuclear power reactor, the energy released in the form of heat which converts water into steam. The steam drives the steam turbine which is mechanically coupled to the electric generator.

The first generation reactors were developed in the 1950-60s and were shut down by 2015. They mostly used natural uranium fuel and used graphite as moderator. Generation-II reactors are mostly still in operation mostly use enriched uranium fuel and cooled and moderated by water. Generation-III are the advanced reactors with higher safety. They are in operation or under manufacture/installation.

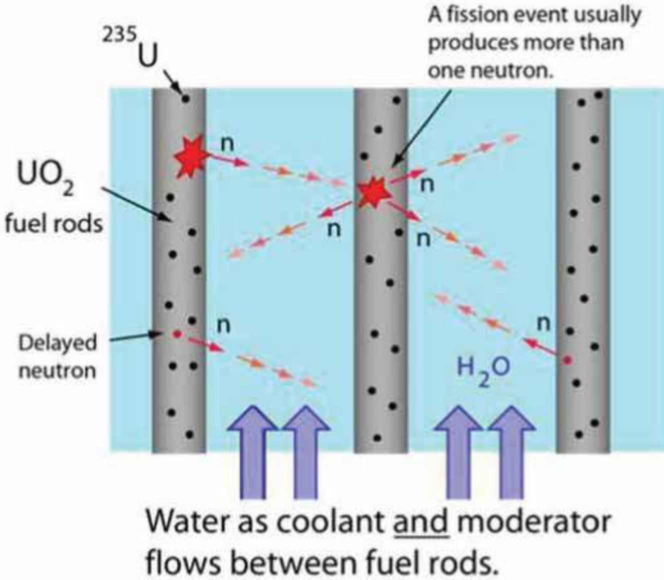

Fig. 3 Fuel, moderator and coolant [3]

The most common type is the pressurized water reactor (PWR) which has water at high temperature and pressure. In a typical PWR, to achieve a pressure of 155 bars, the pressurizer temperature is maintained at 345° C (at a pressure of 155 bars the boiling point of water is 345° C) in its primary cooling/heat transfer circuit, and generates steam in a secondary circuit. In In a boiling water reactor (BWR), the steam is made in the primary circuit above the reactor core, at similar temperatures and pressure. Both types use water as both coolant and moderator, to slow down the speed of neutrons. These are also known as light water reactors. Since water normally boils at 100°C, they have robust steel pressure vessels or tubes to enable the higher operating temperature.

Another type uses heavy water with deuterium atoms, as moderator.

(a) **Components of a nuclear reactor -** There are several components common to most of the different types of reactors:

(i) **Fuel** - Uranium is the basic fuel. Usually pellets of uranium oxide (UO2) are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core. In a 1000 MWe class PWR there might be 51,000 fuel rods with over 18 million pellets. Initially, natural uranium (metal) was used as fuel. Subsequently, natural/enriched UO_2 and PuO_2 (plutonium dioxide) are used in different types of fission reactors. In a new reactor with new fuel, a neutron source is needed to start the fission reaction. The neutron source is generally beryllium mixed with polonium, radium or other alpha-emitter. The alpha particles decay and release neutrons from the beryllium as it turns to carbon-12. A reactor may be restarted with used fuel as there may be enough neutrons to achieve criticality when control rods are removed.

(ii) **Moderator** - The moderator is a material which slows down the speed of neutrons in a nuclear reactor but does not absorb neutrons. Materials used as a moderator are water (also called light water), heavy water, and solid graphite. The moderator is restricted within the containment structure to protect outside from radiation. Material in the core absorbs/slows down the neutrons released from fission so that they cause more fission. It is generally water. However, some reactors use heavy water or graphite as moderator.

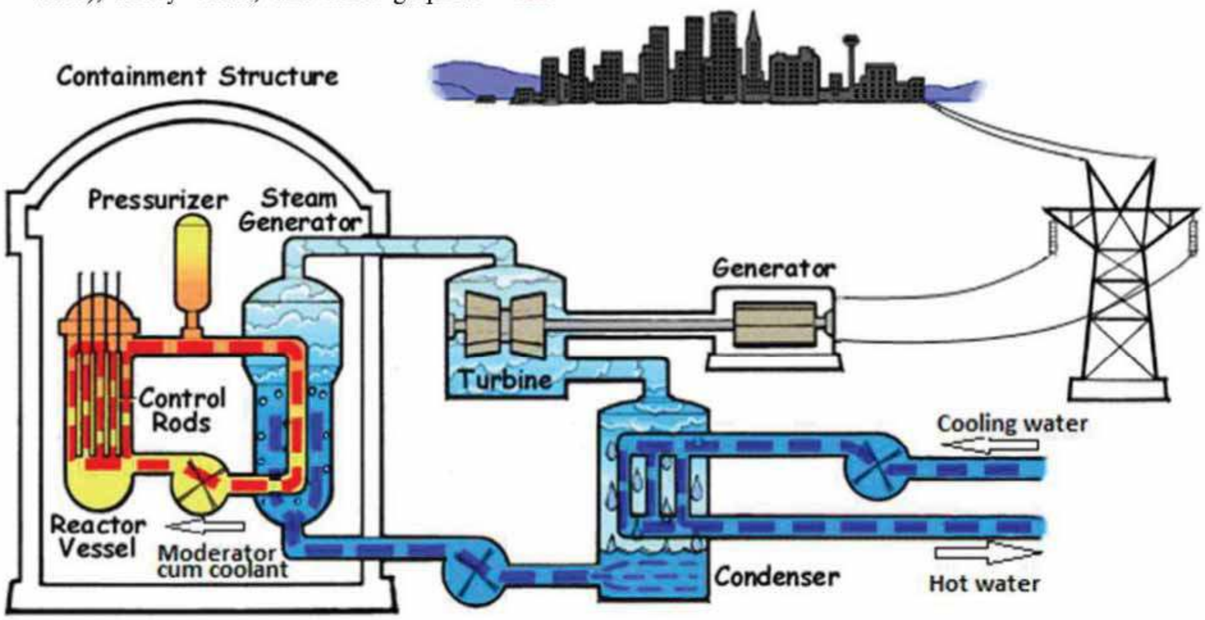

Fig. 4 Pressurized water reactor [4]

(iii) **Control rods -** These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to regulate or halt the reaction.

(iv) **Coolant** - A coolant circulates through the core to take away its heat. Water is the most common fluid used as coolant whereas other coolants used are heavy water, liquid sodium, carbon dioxide, and helium. In a light water reactor, the water used as a moderator also functions as a primary coolant. Except in BWRs, there is secondary coolant circuit where the water is converted into the steam. A PWR has two to four primary coolant loops with forced circulation by pumps. The coolant is circulated in closed loop to control radiation from spreading outside.

(v) **Pressure vessel** -A robust steel vessel houses the reactor core and moderator/coolant.

(vi) **Steam generator -** In pressurized water reactors (PWR & PHWR), a part of the primary coolant is used for converting to steam in a secondary circuit which powers the turbine. There are large heat exchangers which transfer heat from high-pressure primary circuit in PWR to secondary circuit to convert water into steam. The leaking tubes of heat exchanger are plugged.

(vii) **Containment** - A concrete-steel structure, generally about 1 m thick, is provided to form a containment zone around the reactor and associated steam generators. It is designed to limit the effects of radiation within the containment zone. The types of reactors are given in Table-1.

Table 1
Types of Nuclear Reactors [5]

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	304	288.7	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	61	61.8	enriched UO_2	water	water
Pressurized heavy water reactor (PHWR)	Canada, India	48	24.5	natural UO_2	heavy water	heavy water
Advanced gas-cooled reactor (AGR)	UK	10	5.7	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (LWGR)	Russia	11	7.4	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	2	1.4	PuO_2 and UO_2	liquid sodium	none
High temperature gas-cooled reactor (HTGR)	China	1	0.2	enriched UO_2	helium	graphite
TOTAL		437	389.7			

(b) Fuelling a nuclear reactor - If graphite or heavy water is used as a moderator, it is possible to run a power reactor on natural instead of enriched uranium. Natural uranium has the same composition as when it was mined (0.7% U-235, over 99.2% U-238). The enriched uranium has the proportion of the fissile isotope (U-235) which is enhanced by a process called enrichment, from 0.7% to 3.5-5.0%. In this case, ordinary water may be used as a moderator and such reactors are named light water reactors. The light water absorbs neutrons as well as slows them and hence , it is less efficient as a moderator than heavy water or graphite.

During operation, some of the U-238 is changed to plutonium, and Pu-239 ends up providing about one-third of the energy from the fuel.

In most reactors, the fuel used is ceramic uranium oxide (UO_2 with a melting point of 2800° C) and it is mostly enriched. The fuel pellets (usually about 1 cm diameter and 1.5 cm long) are typically arranged in a long zirconium alloy (zircaloy) tube to form a fuel rod. Zirconium is used because it is hard, corrosion-resistant and transparent to neutrons.

A significant industry initiative is to develop accident-tolerant fuels which are more resistant to melting under conditions such as those in the Fukushima accident occurred in 2011, and with the cladding being more resistant to oxidation with hydrogen formation at very high temperatures under such conditions.

Burnable poisons are often used in fuel or coolant to even out the performance of the reactor over time from fresh fuel being loaded for refuelling. These are neutron absorbers which decay under neutron exposure, compensating for the progressive build up of neutron absorbers in the fuel as it is burned, and hence allowing higher fuel burn-up (in terms of GW days per tonne of U). The best known is gadolinium, which is a vital ingredient of fuel in naval reactors where installing fresh fuel is very inconvenient, so reactors are designed to run more than a decade between refuellings (full power equivalent – in practice they are not run continuously). Gadolinium is incorporated in the ceramic fuel pellets. An alternative is zirconium diboride integral fuel burnable absorber (IFBA) as a thin coating on normal pellets.

(c) Fast neutron reactor (FNR) - Some reactors do not use moderator and operate on fast neutrons, generating power from plutonium while making more of it from the U-238 isotope in or around the fuel. While they get more than 60 times as much energy from the original uranium compared with normal reactors, they are expensive to build. Thus, if reactors are designed to produce more fissile material (plutonium) than they consume, then they are called fast breeder reactors (FBR).

(d) Advanced reactors - Generation-IV designs will tend to have closed fuel cycles and burn the long-lived actinides now forming part of spent fuel, so that fission products are the only high-level waste. Of seven designs under development with international collaboration, four or five will be fast neutron reactors. Four will use fluoride or liquid metal coolants, hence operate at low pressure. Two will be gas-cooled. Most will run at much higher temperatures than today's water-cooled reactors.

III NUCLEAR POWER PLANT DISASTERS

The International Nuclear and Radiological Event Scale (INES 0 to INES7) was introduced in 1990 by the International Atomic Energy Agency to indicate the severity of the nuclear disaster. The INES '0' indicates safety significance whereas '7' is the worst case indicating an impact on people and environment due to major release of radioactive material. The major nuclear disasters around the world are given next.

(a) **Fukushima Nuclear Disaster (Japan 2011, INES Level 7) -** On Friday 11 March 2011 the earthquake, which measured 9.0 on the Richter scale, caused a 15 m tsunami that disrupted the power supply resulting in three reactor meltdowns at the Fukushima Daiichi plant. Official figures suggest that more than 1,000 deaths occurred as a result of an evacuation process that displaced more than 1,00,000 people. Subsequent investigations have suggested that the infrastructure and risk forecasting were inadequate for such a devastating natural disaster.

(b) **Chernobyl Nuclear Disaster (Ukraine 1986, INES Level 7) -** The Chernobyl disaster on 26 April 1986 is the worst nuclear power plant accident ever in terms of death toll and cost. A steam explosion destroyed reactor no. 4 at the Ukrainian plant. It resulted in spread of fire and release of huge radioactive waste across Western Europe and also long term fears of increased chances of thyroid cancer.

(c) **Three Mile Island Nuclear Accident (Pennsylvania, USA 1979, INES Level 5) -** The Three Mile Island Unit-2 reactor, near Middletown, Pennsylvania, USA suffered a partial melt down on March 28, 1979. It was caused due to failure of a relief valve after an unplanned shutdown, causing severe damage to the core. However, there were no injuries or discernible health impacts.

(d) **Windscale Fire Nuclear Disaster (Sellafield, UK 1957, INES Level 5) -** On 10 October 1957 a raging inferno swept through the core of Unit-1 nuclear reactor at Windscale, Cumberland (now Sellafield, Cumbria), UK for three days. The accident dumped radioactive contamination across Europe causing risk of cancer cases.

(e) **Kyshtym Nuclear Disaster (Russia 1957, INES Level 6) -** The faulty cooling system resulted in high temperatures which exploded with the force, equivalent of 70-100 tons of TNT. Nuclear fallout spread over 300 km and a week later, 10,000 locals were evacuated from the area.

IV DISPOSAL OF NUCLEAR WASTE

The emergence of nuclear energy offers promising opportunity for low cost and highly efficient energy sources. However, the proper disposal of nuclear waste is still highly challenging. The health concerns and safety issues associated with nuclear waste restrict the widespread use of nuclear energy. Due to its radioactivity and highly hazardous properties, nuclear waste is required to be very carefully stored or reprocessed. The storing and reprocessing of nuclear waste are complicated due to long half-lives of the radioisotopes produced. For example, some of the components can retain half of their dangerous levels even after one million years. This makes the control and management of highly hazardous nuclear waste extremely difficult.

The most common method of nuclear waste disposal is the storage, either using steel cylinders as radioactive shield or using deep and stable geologic formations. However, storage techniques are still under development.

The next generation of nuclear power plants, also called innovative advanced reactors, will generate much less nuclear waste than today's reactors. It is expected that they could be under construction by 2030.

V NUCLEAR FUSION: WORKING AND ISSUES

The nuclear fusion is a process in which one or more light nuclei fuse together to form heavier nucleus in which in there is some loss of mass which is converted into energy given by Einstein's formula: $E = mc^2$, where, E is the kinetic energy in Joules (Nm), m is the mass in kg and c is the velocity of light in m/s.

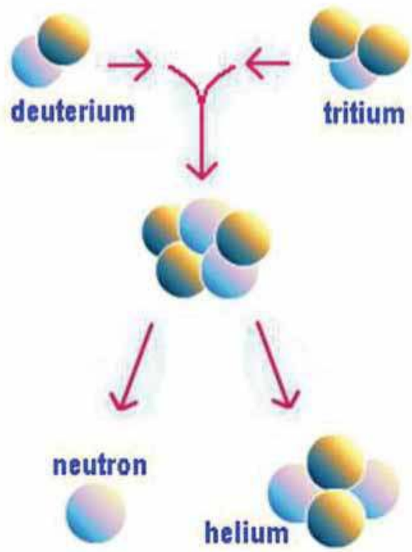

Fig. 5 Nuclear Fusion Process [6]

ITER (International Thermonuclear Experimental Reactor) is an international nuclear fusion research and engineering megaproject aimed at replicating the fusion processes of the Sun to create energy on earth that provides light and warmth and enables life on Earth.

(a) Working of fusion reactor

(i) A few grams of deuterium and tritium (hydrogen) gas are injected into a huge, donut-shaped chamber, called a Tokamak.

(ii) The hydrogen is heated until it becomes a cloud-like ionized plasma.

(iii) The ionized plasma is shaped and controlled by 10,000 tons of superconducting magnets.

(iv) Fusion occurs when the plasma reaches 150 million ℃ — ten times hotter than the core of Sun.

(v) In the fusion reaction, a very small amount of mass is converted to a huge amount of energy.

(vi) The ultra-high-energy neutrons from fusion escape the magnetic cage and transmit energy as heat.

(vii) Water circulating in the walls of the Tokamak absorbs the escaped heat and makes steam. In a power plant, steam will be used to drive turbine.

(viii) Hundreds of Tokamaks have been built; but ITER will be the first to achieve a 'burning' or self-heating plasma.

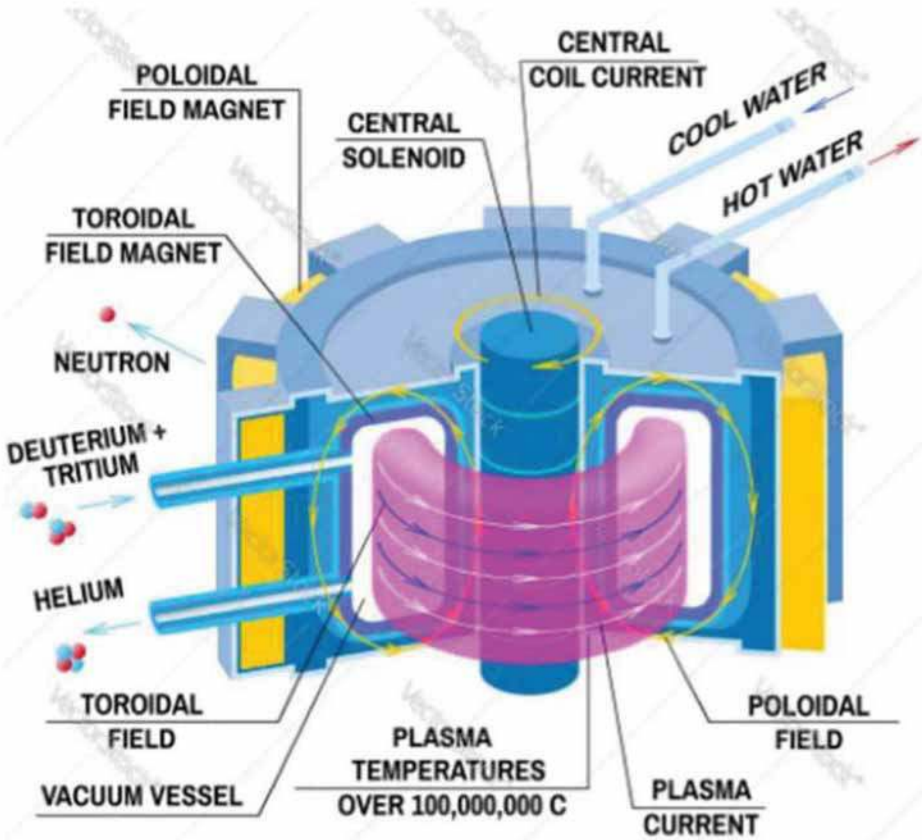

Fig. 6 Thermonuclear fusion reactor [7]

The fuel for fusion is found in seawater and lithium. It is abundant enough to supply humanity for millions of years. A pineapple-sized amount of this fuel is equivalent to 10,000 tons of coal.

The cost of building and operating a fusion plant is expected to be similar to the cost of a nuclear fission plant, but without the large costs and long-term legacy of waste disposal.

After successful completion of ITER project, it is intended to demonstrate that fusion power can be generated sustainably on a commercial scale.

Fusion provides clean, reliable energy without carbon emissions. Fusion is safe, with small quantity of fuel and no physical possibility of a run-away accident with meltdown.

VI NUCLEAR POWER DEVELOPMENT IN INDIA

The importance of nuclear energy, as a sustainable energy resource for our country, was recognized at the very inception of our atomic energy programme. Homi Jehangir Bhabha, the founder Chairman of India's Atomic Energy Commission was the architect of Indian three-stage (thorium) programme based on a closed nuclear fuel cycle. The three stages are:

(a) Three-stage Indian nuclear power programme

Stage-I: Natural uranium fuelled Pressurised Heavy Water Reactors (PHWRs).

Note: The PHWRs are operating with world class performance.

Stage-II: Fast Breeder Reactors (FBRs) utilising plutonium based fuel, and,

Stage-III: Advanced nuclear power systems for utilisation of thorium which is abundantly available in India. It is globally unique.

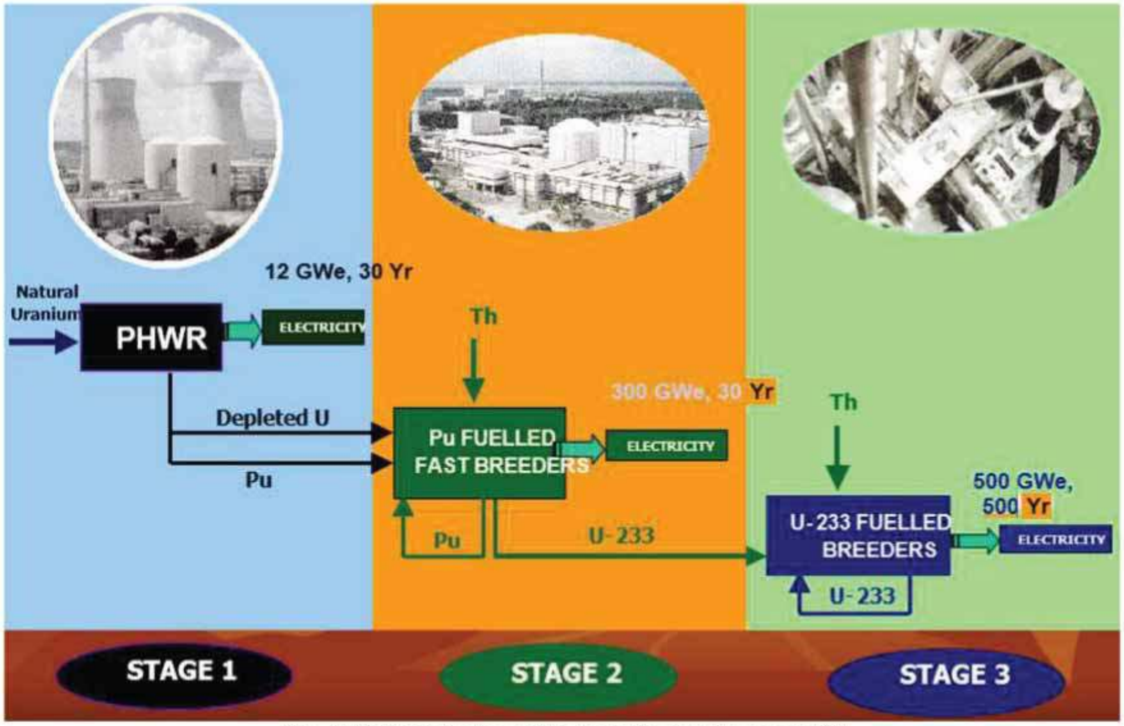

Fig. 7 India's 3-stage Nuclear Power Program [2]

A fertile material is not capable of undergoing fission due to low-energy neutrons. However, it can be converted into fissile material after neutron absorption within a reactor. Thorium-**232** and uranium-238 are the only two naturally occurring fertile materials. After absorbing neutron, U 238 and Th 232 get converted into fissile materials, viz. Pu 239 and U 233, as shown in Figure 6.

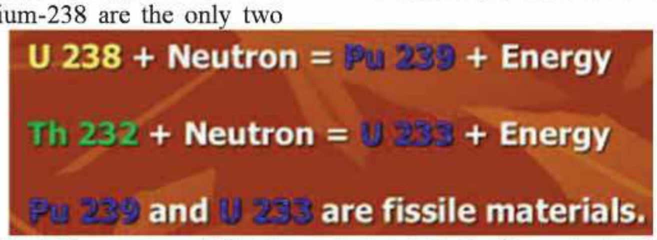

Fig. 8 Conversion of fertile materials into fissile materials [2]

Table 2 shows the status of commissioned nuclear power plants.

Table 2
Nuclear Power Plants in India [8]

No.	Plant	Type	Capacity, MW	Commissioning of first unit
1	Tarapur, Maharashtra	BWR	2x160	1969
		BWR	2x540	2005
2	Kota, Rajasthan	PHWR	1x100	1973
			1x200	1981
			4x220	2000
3	Kalpakkam, Chennai	PHWR	2x220	1984
4	Kaiga, Karnataka	PHWR	4x200	2000
5	Kudankulam, Tamil Nadu	VVER	2x1000	2014
6	Narora, Uttar Pradesh	PHWR	2x220	1991
7	Kakrapar, Gujarat	PHWR	2x220 1x700	1993
		Total = 7380		

BWR = Boiling water reactor,
PHWR=Pressurized heavy water reactor
VVER=Voda Voda Energo Reactor (Water cooled & water moderated)

VII CONCLUSION

The coal deposits are depliting very fast and may last up to turn of century. It is need of time to switch over to a fuel and technology which is capable of supplying base load and is safe with manageable pollution, long lasting. Along with renewable energy sources, Nuclear power may prove to be a good combination for global mankind living creatures, environment.

REFERENCES

[1] Sanskriti Magazine, https://www.sanskritimagazine.com/vedic_science/acharya-kanada-father-atomic-theory/

[2] Introduction to the Three Stage Indian Nuclear Power Programme, NPCIL

[3] Water as moderator, Hyper Physics, Georgia State University. http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/moder.html#c1

[4] Pressurized water reactor, Wikipedia, https://en.wikipedia.org/wiki/Pressurized_water_reactor#/media/File:PressurizedWaterReactor.gif

[5] Nuclear power reactors, world nuclear association, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

[6] http://chemistry.tutorvista.com/nuclear-chemistry/nuclear-fission.html

[7] Thermonuclear fusion reactor diagram way vector image, Vector Stock,

[8] Nuclear Power Corporation of India https://en.wikipedia.org/wiki/Nuclear_Power_Corporation_of_India#Nuclear_plants