Chapter - 9
NUCLEAR ENERGY OPTIONS
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The **sun shall be turned into darkness**, and the moon into blood, before that great and notable day of the Lord come:

The Holy Bible (The Acts 2:20)

While **the sun**, or the light, or the moon, or **the stars**, be not **darkened**, nor the clouds return after the rain:

The Holy Bible (Ecclesiastes 12:2)

Introduction:

Clearly, energy security and energy independence are the two challenges ahead of any nation in this new millennium. The global appetite for energy is simply too great and recurring as well. There is an abrupt need to look something beyond incremental because the additional energy needed is greater than the total of all the energy currently produced. Energy sources are inevitable for progress and prosperity [1].

Energy is inevitable for the very sustenance of human life. There is an abrupt need for vast, imperishable, inexhaustible, long lasting and human friendly energy sources in view of the fast depleting fossil fuel based non renewable energy resources. In this regard can we think of Nuclear energy as a better option? Why? Why not? [2]

The two challenges for human society in the 21st century are the purposeful transition towards a sustainable energy future and also to ensure effective conservation of natural resources across the globe [3].

It has now become imperative to consider what the chances are for saving humanity from energy poverty through controlled power from the nucleus of the atom.

The issue of "*Nuclear Energy Options*" was and is a matter of unending debate with views diverging and opinions contradicting. This can be exemplified from the following two well known quotes:

"Lord, we are especially thankful for nuclear power, the cleanest, safest energy source there is. Except for solar, which is just a pipe dream?" – Homer Simpson

"The nuclear power option - expensive, ineffective, unnecessary and problem-multiplying." – Professor Stuart White

It is generally argued that improving energy efficiency of conventional energy generation process and exploitation of renewable energy sources like wind energy and solar energy can be cheap option for green house gas reduction compared to nuclear energy. Further it appears that nuclear waste management (disposal); decommissioning and proliferation risks involved in Nuclear energy option multiply the existing problem.

The choice of Nuclear Energy hold great promise of inexhaustible energy for manifold applications that can quench human thirst satisfy the need if exploited with wisdom. But the same can be extremely disastrous leading to the destruction of life on earth if used ignorantly.

The July 2005 Indo-US Nuclear deal:

The issue of Nuclear energy gained vitality with the recent remarkable July 2005 Indo-US Nuclear agreement deal according to which the US government should adjust U.S. laws and policies to enable full civil nuclear energy cooperation and trade with India. But all is not good with the deal and the existing obstacles are clear, namely, lifetime fuel guarantees for Indian civilian reactors in return for perpetuity safeguards, the U.S. insistence on "fallback" bilateral safeguards in addition to IAEA (International Atomic Energy Agency) safeguards, the U.S. refusal to allow India to import components and technology for safeguarded reprocessing and enrichment activity, the U.S. refusal to allow reprocessing of spent fuel, India's IAEA safeguards agreement and the timing and nature of the Nuclear Suppliers Group's decision to amend its guidelines to allow commerce with India.

Irrespective of the afore mentioned hindrances it should be noted that India’s advancement in the exploitation of Nuclear energy is not dependent on the mercy of any foreign nation for we have already achieved self-reliance in this field and cooperation from external sources will only be an addition to our efforts in this direction harnessing nuclear energy. Break down of cooperation from other nations is no loss.

The first stage of India's nuclear power programme, presently consisting of 12 Pressurized Heavy Water Reactors (PHWRs), is completely in the industrial domain. As result of the consolidation of the entire work done in the last 50 years, we now have a clearly defined roadmap for future R&D and its commercialization. We have now succeeded in this very frontline technology in all its dimensions. We have different technologies for various applications, namely, Nuclear energy applications in agriculture, health, food security and so on. In addition we have contributed towards nuclear weapons ability in the country. India today is a country with nuclear weapons to ensure its long-term security. At the same time, we have domestic capability to guarantee long-term energy security in a manner that will help in preserving the environment and avoiding the adverse impact of climate change.

Thorium utilization – Indian context:

In Indian context owing to the availability of rich reserves of Thoria development and construction of breeder reactors is of paramount importance and it forms one of the key elements in solving our future energy needs.

Fortunately, India is blessed with natural wealth. Monazite has been used as the source of thorium up to the present time. The deposits are often coloured black by the presence of Magnetite, or red by the presence of garnet. Monazite is characterized by its chemical stability. Solvent extraction process suits well for thorium separation and tributyl phosphate is a particularly promising solvent. This extracts thorium and leaves the rare earths in the aqueous phase. India's vast thorium reserves amount to nearly one-third of world's thorium reserves. Effective utilization of the available vast thorium reserves for harnessing Nuclear energy for the benefit of mankind should be one of the worthy targets of the India's Nuclear Programme. Monazite is the potential source of Uranium. The Monazite has been eroded from igneous rocks and transported by streams to form alluvial deposits. The beach sand of the Indian Malabar and Coromandel coasts are very rich in Monazite and are estimated to contain upto 1, 80,000 tons of Thorium in an easily extractable form. An important Thorium reserve further inland has been discovered also, in the state of Bihar; this is estimated to contain over 3, 00,000 tons of thorium at a concentration of over 10 percent. India has to fall back to its thorium reserves for energy security on a sustainable basis. Road map should be prepared for introducing Thorium (as ThO_2) in place of UO_2 in the blanket zone of FBR's (fast breeders reactors) at an appropriate growth level of installed nuclear power capacity in the second stage. One of the major tasks in hand is to start construction of the thorium fuel based 300 MWe Advanced Heavy water reactor (AHWR). Other large scale deposits of Monazite occur in Brazil, Taiwan, Ceylon and the USA.

Focus Areas:

Very recently while addressing an important conference Shri.Bhattacharjee, Director, BARC, focused on the following issues:

The primary mandates to improve the quality of life of our 1 billion plus population are:

i. To provide energy security by way of generating safe, reliable eco-friendly and economical nuclear power.

ii. Enhance use of radio isotopes and radiation technology in non-power sector for health care, nuclear agriculture and food preservation and industrial applications.

Plans are on the way to induct nuclear energy as primary energy source in the near future i.e., nuclear energy as some of heat for variety of applications such as compact high temperature reactor for small unattended power packs for electricity generation in remote areas that are not connected to the grid systems or for the production of hydrogen from H_2O using thermo chemical means as an environment friendly alternative to hydrocarbon fuels for our transportation sector or even for refinement of low grade coal and oil deposits to high grade fossil fuel.

Nuclear Technology – Scientific Contribution:

Very many scientists have toiled for years and offered sacrifices to generate fundamental knowledge related to Nuclear Science and Technology. It is inevitable that their efforts and achievements are remembered before start of any preliminary discussion on Nuclear Energy options.

Stalwarts in the field of Nuclear Science:

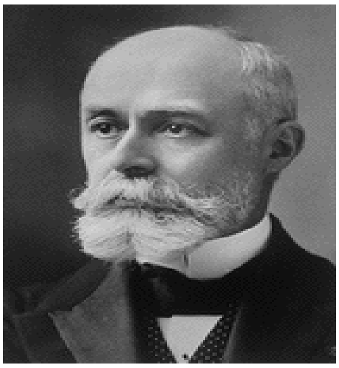
Ernest Rutherford, (1871-1937), Great Britain:

Ernest Rutherford was awarded the Nobel Prize in Chemistry 1908 for his investigations into the disintegration of the elements, and the chemistry of radioactive substances. He was the first to postulate the concept of Nucleus which is one of the greatest contributions to science. He was the first to deliberately transmute one element into another. In 1989 he reported the existence of alpha and beta rays in uranium radiation and indicated some of their properties. In 1910 his investigations into the scattering of alpha rays and the nature of the inner structure of the atom which caused such scattering led to the postulation of his concept of “nucleus”. According to him practically the whole mass of the atom and at the same time all positive charge of the atom is concentrated in a minute space at the centre.

Niels Henrik David Bohr, 1885-1962, Denmark:

Niels Bohr was awarded the Nobel Prize in Physics 1922 for his contribution in the investigation of the structure of atoms and of the radiation emanating from them. He succeeded in working out and presenting a picture of atomic structure. He proposed liquid drop model for nuclear structure. This particular model permitted the understanding of the mechanism of nuclear fission.

Antoine Henry Becquerel, 1852 – 1908, Paris:



Discovered Radioactivity

Awarded the Nobel Prize in Physics, 1903

Becquerel was born in Paris on 15th December, 1852. In 1982 he was appointed as Professor of Applied Physics in the Department of Natural History at the Paris museum. Becquerel's earlier work was related to polarization of light, the phenomenon of phosphorescence and the absorption of light by crystals.

In 1896, Henri Becquerel observed the blackening of a photographic plate placed unintentionally close to a uranium preparation. This has led to the serendipitous discovery of radioactivity. The phenomenon was then wholly incomprehensible and subsequently led to series of other spectacular discoveries. The new results thus obtained formed the basis of modern concepts and the birth of Nuclear Science. Marie Sklodowska Curie, a Polish pupil of Becquerel, proposed the name radioactivity. Becquerel was awarded the Noble prize for Physics in 1903 for his discovery of spontaneous radioactivity. Pierre and Marie Curie shared the Noble prize with Becquerel for their study of the Becquerel radiation.

Marie Sklodowska Curie, 1867-1934, Poland:

1903 Nobel Prize in Physics

1911 Nobel Prize in Chemistry

Discovered elements radium and polonium

Coined term "Radioactivity"

Marie Curie was born in Warsaw on 7th November, 1867. Her early researches, together with her husband Pierre Curie, were often performed under difficult conditions, with poor laboratory arrangements. Pierre and Marie Curie observed naturally

Occurring pitch blend to be many more times radioactive than expected as per the uranium content. They were right in their comprehension that some unknown element far more radioactive than uranium must be present in naturally occurring pitch blend. Knowing fully well, the road ahead it dark and gloomy, they determined to go ahead with the faith in their reasoning in spite of the very fact the no financial support existed. The Curies attempted to isolate the mysterious element. They worked in a shed with a simple electroscope developed

by Pierre himself for differentiating the ‘active’ fraction from the rest. Their agonizingly prolonged toil was not in vein and they succeeded in separating and isolating not one but two new intensely radioactive elements from the bismuth and barium fractions. The former was named Polonium, after Marie’s native country and the other Radium (1898). The isolation of these elements present in no more than some mg in a tonne of the ore is not only a remarkable triumph of their prediction, but a chemical engineering achievement unparalleled in the history of Science. Together with her husband, Madam Curie was awarded Nobel prize for Physics in 1903 for their study into the spontaneous radiation discovered by Becquerel. In 1911 she received the second Nobel prize for Chemistry in recognition to her work in radioactivity.
Madam Curie was held in high esteem and admiration by Scientists throughout the world.

Irene Joliot - Curie, 1897-1956, France:

Discovered Artificial Radioactivity

1935 Nobel Prize in Chemistry

Irene Curie was born on 12th September, 1897 in Paris. She was the daughter of Pierre and Marie Curie. In 1926 she was married to Frederic Joliot. Her Doctoral studies were focused on the alpha rays of Po. She carried out important work along with her husband Frederic on natural and artificial radioactivity, transmutation of elements. Soon after the discovery of the Neutron, in a series of experiments, Irene and Frederic Joliot-Curie studied the effects of bombarding light elements like B, Al and Mg with high energy alpha particles from Po. They observed anomalies when Al^{27} is bombarded with α particle ($_2He^4$). In all the cases they observed the emission of neutrons and positrons. From the considerations of the conservation of mass and charge the recoil product should be the light isotope of Phosphorous (P^{30}) which was not know at the time (the natural element being monoisotopic P^{31}). Also, the moment the α source was removed, the emission of neutrons stopped. But the emission of positrons continued over well measurable periods. The intensity of the positron emission was observed to decay exponentially with time. The half-life was found to be 3 minutes. Thus a true artificial radioactive source is found (P^{30}) for the first time. Other immediate studies were Mg^{24} and B^{10}

which resulted in the formation of radioisotopes Si^{27} and N^{13}. The toiling efforts of Irene and Frederic Jaliot-Curie resulted in the synthesis of P^{30}, Si^{27} and N^{13}, the first three radioisotopes prepared artificially. Now radioactivity is no longer restricted to few naturally occurring elements as Ra, U and Th. Radioisotopes find diverse applications in research, medicine, agriculture and industry. She shared the Nobel Prize in Chemistry for 1935 with Frederic Joliot in recognition of their synthesis of new radioactive elements.

Lise Meitner, 1878-1968, Austria:

Most significant woman scientists of the 20th century

Discovered the element Protactinium (91)

First to explain the theory of nuclear fission

Germany's first woman Physics professor

Artificial element 109 named in her honour

Lise Meitner was born on 27th October, 1968 in Austria. She studied Radioactivity and Nuclear Physics. In 1917, Lise Mitner and Otto Hahn discovered the first long-lived isotope of the element Protactinium. In 1923, she discovered the cause of the emission of electron from surfaces with 'signature' energies. (Auger effect). With the discovery of the neutron by James Chadwick in 1932 speculation arose in the scientific community that it might be possible to create elements heavier than Uranium in the laboratory. A scientific race began between Ernest Rutherford in Britain, Irene Joliot – Curie in France, Enrico Fermi in Italy, and the Meitner-Hahn team in Berlin. None suspected that this research would create in nuclear weapons.

James Chadwick, 1891-1974, Great Britain:

The Nobel Prize in Physics 1935 for the discovery of Neutron – An epoch making discovery.

Chadwick prepared the way towards the fission of U-235 leading to the creation of the atomic bomb.

Chadwick proved the existence of neutrons which constitute one of the elementary particles of atom apart from proton and electron. It is present inside the nucleus. Neutron is devoid of any charge and so it need not overcome any electric barrier (electric forces present in heavy nuclei) offered by heavy atoms. As a result neutrons can penetrate and split the nuclei of even the heaviest elements.

Enrico Fermi, 1901-1954, Italy:

The Nobel Prize in Physics 1938

Evolved the theory of ß-decay, 1934

First to device and design an atomic pile

Enrico Fermi was born in Rome on 29th September 1901. He was awarded the Nobel Prize in Physics 1938 for his demonstrations of the existence of new radio active elements produced by neutron irradiation and for his related discovery of nuclear reactions brought about by slow neutrons. He evolved the β-decay theory in 1934. He demonstrated that nuclear transformations occur in almost every element subjected to neutron bombardment. He saw the possibility of emission of secondary neutrons and of a chain reaction. He has proceeded to work with tremendous enthusiasm which ultimately led to the atomic pile and the first controlled nuclear chain reaction.

Glenn Theodore Seaborg, 1893-1981, USA:

The Nobel Prize in Chemistry 1951

G. T. Seaborg was born in Rome on 29th September 1901.

He was co-discoverer of Plutonium and all further Tran uranium elements through element 102. Seaborg and his colleagues are responsible for the identification of more than 100 isotopes of elements through out the periodic table. He was awarded Nobel Prize in Chemistry for the discovery of the transuranic elements.

Homi J Bhabha, 1909 – 1966, India:

Homi Jehangir Bhabha is the Architect of India's Nuclear Programme. He is an outstanding scientist and a brilliant Engineer. Bhabha was indeed a perfectionalist. This worthy son of Mother India was born on 30th October, 1909.

In the words of the inventor of Cloud Chamber C.T.R. Wilson: “Scientist, engineer, master-builder and administrator, steeped in humanities, in art and music, Homi was a truly complete man."

The name 'Meson' now used for a class of elementary particles (new particle found in cosmic radiation with a mass intermediate between that of electron and the proton), was in fact suggested by Bhabha. He established two great research institutions namely the TIFR and BARC and from this we can know how great visionary he was.

To remember his own views about life let us look at a quote of Bhabha.

"I know quite clearly what I want of my life. Life and my emotions are the only things I am conscious of. I love the consciousness of life and I want as much of it as I can get. But the span of one's life is limited. What comes after death no one knows. Nor do I care. Since, therefore, I cannot increase the content of life by increasing its duration; I will increase it by increasing its intensity. Art, music, poetry and every thing else that consciousness I do have this one purpose - increasing the intensity of my consciousness of life." Unfortunately Bhabha died prematurely in a suspicious air crash on Mount Blanc on 24th January, 1966. It was indeed an irreparable loss to the Nation as a whole.

A. P. J. Abdul Kalam, (1931 -), India:

Avul Pakir Jainulabdeen Abdul Kalam, the most distinguished scientist of India was born on 15th October, 1931 at Rameswaram in Tamil Nadu. He got specialized in Aeronautical Engineering from Madras Institute of Technology. He mastered himself in missile launch vehicle technology. He led to the weaponisation of strategic missile systems and the Pokhran – II nuclear tests which made India a nuclear weapon state. He took up a mission to ignite the young minds for national development by meeting high school students across the country. Dr. Kalam became the 11th president of India. He received the highest civilian award Bharat Ratna in the year 1997.

India's Nuclear Policy:

Our policy is based on complete disarmament and no first use. India has always stood for nuclear non-proliferation and its nuclear programme was meant for peaceful purposes in the field of energy for civil purposes, agriculture, medicine and research.

Nuclear Reactions:

Nuclei remain intact in a vast majority of chemical reactions. Some space should be devoted here for Alchemy and Alchemists since modern Chemistry has originated from Alchemy. Alchemy is as old as human civilization. The Greek word 'chemia' appeared in the fourth century. Later Arabic prefix 'al' was added to it. Thus the word Alchemy signifies art of chemistry in general. Alchemy was a mixture of mystical, speculative thought and practical laboratory techniques of chemistry and metallurgy. The main aim of Alchemists was the transformation of base metals in to silver and gold (artificial transmutation) which can in no way achieved by any of the known chemical reactions. Development and understanding of Nuclear Science made it possible to artificially transmute one element in to another. It is now known that a few nuclei under ordinary conditions, and all nuclei under special conditions, undergo changes leading to nuclear reactions. Such reactions in which nucleus undergoes spontaneous change or interact with other nuclei of lighter particles resulting new nuclei and one or more lighter particles are called nuclear reactions. There are striking differences between ordinary chemical reactions and nuclear reactions and the differences are summarized below.

i. Chemical reactions depend upon the number of extra electron while nuclear reactions are independent of the electrons but depend on the nature of the nucleus.

ii. Chemical reactions involve some loss, gain or overlap of outer orbital electron of the two reactant atoms. Nuclear reactions involve emission of some light particles (α, β, positron and few others) from the nucleus of the atom to form another element.

iii. The chemical reactivity of an element is dependent on the nature of the bond present in the concerned compound. Where as the nuclear reactivity of an element is independent of its state of chemical combination. For instance, radium whether present as such or in the form of its compound shows similar radioactivity.

iv. A chemical reaction is balanced only in terms of mass where as a nuclear reaction must be balanced in terms of both mass and energy.

v. The energy change occurring in nuclear reactions is very high as compared to that in chemical reactions. The energy involved in a chemical reaction is expressed in kcal/mole where as in nuclear reactions the energy is expressed in MeV per nucleus.

vi. The chemical reactions are dependent on temperature and pressure while the nuclear reactions are independent of external conditions.

Energy from Nuclear Fission:

Among several nuclear reactions known, for instance, nuclear fission, nuclear fusion, radioactive decay, artificial transmutation, photonuclear reactions, radioactive capture, evaporation, spallation and many others, nuclear fission has the greatest practical significance and has been exploited to the greatest extent for energy related applications relative to other reactions.

The staggering amount of energy released during the process of fission is illustrated below with respect to the fission of ^{235}U caused by thermal neutrons where in the fission fragments are ^{95}Mo and ^{139}La. The exact mass numbers of reactants and products are shown below each of the reactants and products.

$_{92}U^{235}$ + $_{0}n^{1}$ $\rightarrow$ $_{42}Mo^{95}$ + $_{57}La^{139}$ + 2 $_{0}n^{1}$ + energy

235.0439 + 1.0087 94.9057+ 138.9061+2.0174

236.0526 235.8292

Mass loss, $\Delta m = 0.2234$ amu

Fission energy = 931 Δm = 208 MeV

From where this figure 931 suddenly appeared? What is special about it?

The energy equivalent to 1 atomic mass unit (amu) is 931 MeV.

The mass of standard carbon atom ($_{6}C^{12}$) is taken to be 12 amu.

So, mass of $_{6}C^{12}$ atom = 12 amu

1 amu = 1/12 x mass of $_{6}C^{12}$ atom

1 mole = 12 g

6.023×10^{23} atoms = 12 g

1 atom = $12/6.023 \times 10^{23}$ g

1 amu = $1/12 \times 12/6.023 \times 10^{23}$ g

$= 1.66 \times 10^{-24}$ g $= 1.66 \times 10^{-27}$ kg

According to Einstein's mass-energy relation:

$E = mc^2$

E, energy in Joules

M, mass in kg

C, velocity of light in m/sec

$E = 1.66 \times 10^{-27} \times (2.99 \times 10^{8})^2$ J

1 eV = 1.602×10^{-19} J

$E = 1.66 \times 10^{-27} \times (2.998 \times 10^{8})^2/1.602 \times 10^{-19}$ eV

$= 1.66 \times 2.998 \times 2.998 \times 10^{8}/1.602$

$= 9.3134 \times 10^{8}$ eV

= 931.3 MeV

This total energy of about 200 MeV is found to be distributed between the products of fission as follows:

Table 1. Energy from fission

Fission product	**Energy carried, MeV**

Light fragment Heavy fragment	100 67
2.5 neutrons each of 2 MeV energy	5
γ photons	12
β^- and neutrinos	16

Nuclear Fission:

Fission is a process in which a nucleus excited by a neutron or by other means breaks into two fragments of comparable sizes. A significant amount of matter of atomic nucleus is annihilated releasing the corresponding on a scale totally unknown before

The process of nuclear fission was discovered by Otto Hahn and F. Strassman in January 1939. It marked the beginning of the nuclear age. The discovery of neutron by James Chadwick in 1932 can be termed as the origin of experiments that resulted in the discovery of Nuclear Fission. Soon after the discovery of fission by Hahn and Strassman, Lise Meitner and O. R. Frisch developed a theory for the phenomenon. They proposed that upon neutron capture to a point of overcoming the force of surface energy, distortion of the excited nucleus takes place resulting in a splitting of the nucleus into fragments of comparable masses [4].

The reaction of nuclear fission is schematically shown in Fig. 1. Fission occurs when fissionable nucleus captures a neutron. The internal balance between neutrons and protons in the nucleus is upset and it splits into two lighter nuclei. On the average 2-3 neutrons are emitted. The mass of the resulting products is less than the sum of the masses of the original nucleus plus the captured neutron and the difference appears as energy according to Einstein's equation ($E=\Delta mc^2$, where Δm is the mass loss involved in a particular nuclear reaction, c is the velocity of light). If the released neutrons are captured by other fissionable nuclei more fission events occur. When the reaction becomes self-sustaining so that one fission triggers at least one more fission, the phenomenon is termed as a chain reaction.

If the amount of U-235 is small, most of the neutrons will escape from the surface and the reaction will stop. Therefore, a critical mass of metallic uranium is necessary in order to start and sustain a chain reaction. The critical mass of U-235 has been found to be between 1 to 100 kg.

The basic principle of an atomic bomb is the chain reaction. At the time of explosion two samples each of sub critical mass, but whose total mass exceeds the critical mass, are brought together by the use of ordinary explosives. Once these sub critical masses come together, a chain reaction starts releasing a large amount of energy. One gram of U-235 evolves upon fission about 2 x 10^7 kcal of energy.

Let us take the fissionable nucleus, U^{235}, as a specific example.

In general the fission reaction resulting from absorption of neutron by U235 can be written as shown below. The two fission fragments are labeled as F_1 and F_2 to indicate that many possible ways of splitting do exist.

${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{A1}F_1^{Z1} + {}_{A2}F_2^{Z2} + \tilde{\upsilon}\,{}_0n^1$ + energy

When uranium isotope – 235 is bombarded with slow neutrons, U^{236} is formed by the capturing of neutron. The U^{236} being unstable break up into two fragments besides releasing two or three neutrons.

${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236} \rightarrow {}_{56}Ba^{141}\,(F_2) + {}_{36}Kr^{92}\,(F_1) + 2\text{-}3\ {}_0n^1$ + 200 MeV

${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236} \rightarrow {}_{54}Xe^{139} + {}_{38}Sr^{95} + 2\ {}_0n^1$ + 200 MeV

${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236} \rightarrow {}_{54}Xe^{141} + {}_{38}Sr^{92} + 2\ {}_0n^1$ + 200 MeV

${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236} \rightarrow {}_{52}Te^{137} + {}_{40}Zr^{97} + 2\ {}_0n^1$ + 200 MeV

As seen above the fission fragments (F1) and (F2) is not a unique pair but could be one of about 30 possible pairs such that the mass number of lighter fragments (F_1) ranges from about 85 to 105 and that of heavier fragments (F_2) from about 150 to 130.

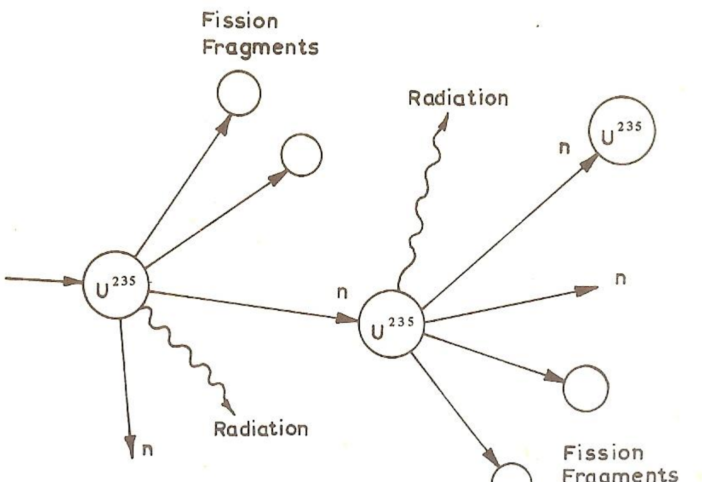


Fig. 1. Schematic of U^{235} fission [5]

Mechanism of Nuclear Fission:

In certain heavy elements like U and Pu absorption of a neutron results in the splitting of the nucleus in to two massive fragments. The sequence of events involved in the process is depicted in Fig. 2. As illustrative example the reaction of U-235 with neutron is considered.

In stage A, the neutron approaches the U-235 nucleus. In stage B, the U-236 nucleus has been formed, in an excited state. The excess energy in some interactions may be released as a gamma ray. More frequently, the energy causes distortions of the nucleus into a dumbbell shape, as in stage C. The parts of the nucleus oscillate in a manner analogous to the motion of a drop of liquid. Because of the dominance of the electrostatic repulsion over nuclear attraction, the two parts can separate, as in stage D.

They are then called fission fragments, bearing most of the mass-energy released. They fly apart at high speeds carrying some 166 MeV of kinetic energy out of the total of around 200 MeV released in the whole process. As the fragments separate, they lose atomic electrons, and the resulting high-speed ions lose energy by interaction with the atoms and molecules of the surrounding medium. The resultant thermal energy is recoverable if the fission takes place in a nuclear reactor. Also shown in the diagram are the gamma rays and fast neutrons that come off at the time of splitting.

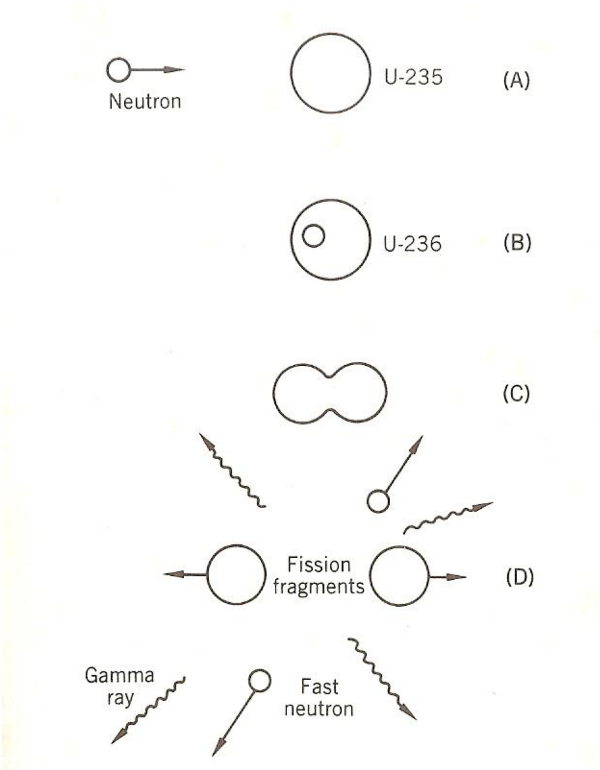


Fig. 2. The Fission Process [6]

Fission energy:

As in all radioactive decays, Nuclear Fission is also accompanied by mass loss and the liberation of corresponding amount of energy. The mass loss in nuclear fission comes to around 0.2 amu (atomic mass units) which is roughly 100 times greater than the mass loss observed in all other types of radioactive decay.

Nuclear reactors:

A nuclear reactor is a device designed to produce and sustain a long term controlled fission chain reaction. The words sustain and long term should be noted with some emphasis, since they indicate the fundamental difference between a nuclear reactor and an atomic bomb.

Fissioning of a gram of uranium yields approximately one million times as much energy as is released by the same quantity of uranium undergoing a chemical reaction, eg. Oxidation. This comparison between nuclear energy and chemical energy is a major feature unique to nuclear reactors.

There is only one naturally occurring isotope which fissions readily. This is the isotope of uranium having an atomic weight of 235. It constitutes about 0.7% of natural uranium (balance U-238). There are two other fissionable isotopes of practical interest, Pu-239 and U-233 which can be produced as a result of neutron reactions with U-238 and Th-232 respectively.

Components and materials of Nuclear Reactors:

In brief, the lighter elements such as H, Be and C act as suitable neutron moderators. Most of the elements near the centre of the periodic table appear as fission products. The heavier elements are either potential nuclear fuels or are produced by neutron capture in the fuel during operation of a reactor. Many of the transition metals make suitable construction or container materials for nuclear reactors. Many elements such as fluorine, as UF6, find a unique application in the industry. An elaborate account of the components of the nuclear reaction is placed below:

The Fuel:

Special nuclear material (SNM) – Where do they come from?

SNM is defined by Title I of the atomic energy act of 1954 as Pu, U-233 or uranium enriched in the isotopes of U-233 or U-235. The definition includes any other material which the commission determines to be special nuclear material, but does not include source material.

U-233 and Pu-239 do not occur naturally. They can be formed in nuclear reactors and extracted from the highly radioactive spent fuel by chemical separation. U-233 can be produced in special reactors that use Thorium as fuel. Pu-239 can be produced in reactors using U-238 or U-235 fuel. Uranium enriched in uranium 235 is created by an enrichment facility. U-233 is an entirely man-made isotope. Its importance stems from the fact that it has a high cross section for fission by thermal neutrons. Its fission cross sections are comparable to that of the other fissile nuclides like U-235 and U-239. The precursor for U-233 is the widely occurring monoisotopic Th-232. India has an abundant supply of Th-232 in the form of rich monazite sand of karalla.

Plutonium – Why do world nations crave for this?

Plutonium (Pu) is strategically the most important element of the 20th century. It is entirely man-made atom by atom, first in μg and now in kg amounts and stockpiled in tones, in sub critical amounts.

$U^{238} + {}_0n^1 \rightarrow U^{239}$ (β decay) $\rightarrow Np^{239}$ (β decay) $\rightarrow Pu^{239}$ (α emitter, half life = 2.4×10^4 years) $\rightarrow U^{235}$

Pu-239 is employed as nuclear fuel on account of its high neutron absorption cross section (cross section for fission by thermal neutrons). It is used as fuel in fast breeder reactor, where it is bred from U^{238}. It is used as an atom bomb element.

Uranium enrichment:

Three isotopes of uranium occur naturally and their relative abundances (in atomic percent) are as follows:

${}_{92}U^{234}$ (light weight atom) - 0.006%

${}_{92}U^{235}$ (middle weight atom) - 0.714%

${}_{92}U^{238}$ (heavy atom) - 99.28%

The fuel for nuclear reactors has to have a higher concentration of uranium-235 than exists in natural uranium ore. This is because U-235 is the key ingredient that starts a nuclear reactor and keeps it going. Normally, the amount of U-235 isotope is enriched from 0.7 % of uranium mass to 5 %. Several different processes are used to enrich uranium. The important methods among them being *Gas diffusion* and *Gas centrifuge*. Separation of U-235 from natural uranium is an outstanding example of isotope separation. The separation process relies upon the slight difference in the rate of diffusion through a membrane (Graham's law of diffusion) of the hexafluorides namely $U^{235}F_6$ and $U^{238}F_6$. Fortunately the situation is not complicated by the variation in the isotopic weights of fluorine since the only naturally occurring isotope of fluorine is F^{19}.

Gas diffusion method:

In the gaseous diffusion enrichment plant, the solid uranium hexafluoride (UF_6) from the conversion process is heated in its container until it becomes a liquid. The container becomes slightly pressurized as the solid melts. Because the container is not completely full UF_6 gas then fills the top of the container. The UF_6 gas is slowly fed into the plant's pipelines where it is pumped through special filters called barriers or porous membranes. The holes in the barriers are so small that there is barely enough room for the UF_6 gas molecules to pass through. The isotope enrichment occurs when the lighter UF_6 gas molecules (with the U-234 and U-235 atoms) tend to diffuse faster through the barriers than the heavier UF_6 gas molecules containing U-238. One barrier is not enough to do the job. It takes many hundreds of barriers, one after the other, before the UF_6 gas contains enough U-235 to be used in reactors. At the end of the process, the enriched UF_6 gas is with drawn from the pipelines and condensed back into a liquid that is poured into containers. The UF_6 is then allowed to cool and solidify before it is transported to fuel fabrication facilities where it is turned into fuel assemblies for nuclear power reactors.

Gas centrifugation method:

The gas centrifuge uranium enrichment process uses a large number of rotating cylinders in a series. These series of centrifuge machines, called trains. They are interconnected to form cascades. In this process, uranium hexafluoride (UF6) gas is placed in a rotating drum or cylinder and rotated at a high speed. This rotation creates a strong gravitational field so that the heavier gas molecules (with U-238) move toward outside (out let at the bottom) of the cylinder and the lighter gas molecules (containing U-235) collected closer to the centre. The stream that is slightly enriched in U-235 is withdrawn and fed into next higher stage, while the slightly depleted stream is recycled back into the next lower stage. Significantly more U-235 enrichment can be obtained from a single unit gas centrifuge than from a single unit gaseous diffusion barrier.

Moderator:

Material which helps the neutrons lose energy and keeps them in custody until they are relatively safe from capture by U-238 is known as moderator. It is obvious that the moderator must not absorb too many neutrons or the reaction will stop. Fast neutrons released by fission are not as easy to catch as are slower neutrons, so we allow them to wander around in the moderator and reduce their energy to that corresponding to the ambient temperature. These neutrons are then in thermal equilibrium with the atoms or molecules of the moderator. Such neutrons are called thermal neutrons and have kinetic energies in the order of 0.025 eV, implying a speed of about 5000 mph. The probability that a U-235 nucleus will fission is about 300 times greater with a slow (thermal) neutron than with a fast neutron. In more technical terms, it can be stated that the fission cross-section of natural uranium increases from about 0.015 barns at a neutron energy of 1 MeV to 3.9 barns at thermal neutron energy. Thus to produce a neutron chain reaction in natural uranium it is necessary to add a moderating material which will slow down the neutrons by collision with the moderator nuclei. Suitable moderators are light and heavy water, carbon (graphite), beryllium, and beryllium compounds.

The most widely used moderators are heavy water (D_2O) and graphite. Light water can be used but it has high neutron absorption cross section compared to deuterium. When D_2O is moderator, since the neutron absorption cross section is low, the U-235 content of the fuel is correspondingly smaller.

Natural graphite has a density of 2.26 g/cc where as artificial graphite has a lower density of 1.6 – 1.7 g/cc. This lower density implies a comparatively high porosity. Unfortunately, this is a considerable disadvantage since the amount of surface available for oxidation reactions is increases.

Nuclear Reactors – Control:

Safety is given no less priority in the design and fabrication of the Nuclear reactors meant for a sustained chain reaction. In this regard, Control rods play a prominent role. It can be regarded as one of the poisons towards neutrons and these can be employed at the call of the situation. They have great capacity to absorb neutrons. They are arrestors of neutrons. The number of fissions occurring per second in the nuclear reactions and thus the chain reactions can be regulated by adjusting the position of these rods.

What materials can function as control rod poisons?

What criteria a given material has to satisfy for it to be employed as a control rod?

The major requirements that should be satisfied are. High neutron absorption, adequate strength, low mass (for rapid movement), corrosion resistance, stability under heat and radiation and satisfactory heat-transfer properties.

The possible materials for control rods are:

Boron, Cadmium, Hafnium, Rare earths, Europium, Gadolinium, Samarium, Dysprosium, Erbium and Lutetium. Elements with relatively high thermal neutron absorption cross section are Cd (2400 barns), Boron (750 barns), Hafnium (115 barns), Iridium (440 barns), Mercury (300 barns), and mixtures of rare earths. Because Hafnium, Indium and the rare earths were quite expensive and Mercury presented engineering difficulties early emphasis was on Cd and B.

Unfortunately, neither of these, in elemental form, meets all the requirements. In more recent years, interest in Hf and the rare earths has greatly increased.

The Hafnium:

Hafnium is found associated with Zirconium in all its minerals, and is normally obtained by removing it from Zr. In general Hafnium is similar to Zr and Ti in its properties, corrosion resistance, fabrication etc. Unlike Zr, however, it is not sensitive to small amounts of impurities such as Nitrogen. Although the thermal neutron absorption cross section is relatively low, Hf is highly effective as a control because of its large epithermal resonance-capture cross section. The major advantage of hafnium over B and Cd is that is, doesn't need to be incorporated in some other materials, since it has more than adequate strength and stability in itself.

Coolants:

The heat produced in the reactor is extracted out by coolants. The heat can be used to convert water to high pressure steam which drives the turbine and the latter in turn drives the generator. Light water, CO_2, Helium and liquid sodium can be used as coolants.

Classification of Nuclear Reactors:

Depending on the purpose, neutron energy, moderator and coolant, fuel arrangement and structure materials reactors can be classified into various types the main purpose being power, research, and breeder and so on.

Depending on the energy of the neutron used to induce fission the reactors can be classified into either fast reactor or thermal reactors. In a fast reactor most of the neutrons are in the energy range of 0.1 – 1 MeV. The neutron remains at high energy because there is relatively little material present to cause them to slow down. In contrast, thermal reactor contains a good neutron moderating material. In these reactors, the bulk of the neutrons have energy in the vicinity of 0.1 eV.

Nuclear power plants:

The talk of building Nuclear power plants is reviving world over because of their low emissions of green house gases in the generation process. Nuclear energy is a way to generate heat using the fission process of atoms. A Nuclear power plant converts the heat into electricity. The purpose of a nuclear power plant is to produce or release heat and boil water. It is designed to produce electricity. It should be noted that while there are significant differences, there are many similarities between power plants and other electrical generating facilities. Uranium is used for fuel, in general, in nuclear power plants to make electricity. The main difference between a nuclear power plant and other kinds of power plants (coal, oil, gas) is that at a nuclear plant, the heat used to make the steam is produced by fissioning atoms. Fission is the splitting of atoms into smaller pieces, caused by neutrons. These smaller pieces (in crude terminology) strike other atoms, releasing energy. When this process continues it is called a chain reaction.

Broadly there are three types of nuclear power plant reactors, namely, burner reactors, converter reactors, and breeder reactors.

Both Pressurized water reactors and boiling water reactors are two types of light water reactors.

Breeder reactors:

Breeder reactors produce more fissionable material than they consume. Breeder fuel consists of a mixture of both fertile ($U^{238,}$ Th^{232}) and fissile ((Pu^{239} , U^{233}) materials. The number of neutrons released is sufficient to propagate the fission reaction and to produce more fissionable materials (Pu^{239}) by the conversion of fertile isotopes to fissile isotopes.

Principle of breeding:

As seen above an appropriate mixture of Pu^{239}(U^{233}) and U^{238}(Th^{232}) should be employed as fuel in breeder reactors. Let us consider one such reactor. It is possible to create conditions such that out of the three neutrons released from the fission of each fissile atom (Pu^{239} or U^{233}) one of the neutrons is used up in propagating the fission chain by interacting with other fissile atom (Pu^{239} or U^{233}). At the same time the remaining two neutrons will be available for transmuting U^{238} or Th^{232} in to two new fissile atoms of Pu^{239} or U^{233} by the reactions shown below.

${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239}$ (β decay) → ${}_{93}Np^{239}$ (β decay) → ${}_{94}Pu^{239}$

${}_{90}Th^{232} + {}_{0}n^{1} \rightarrow {}_{90}Th^{233}$ (β decay) → ${}_{91}Pa^{233}$ (β decay) → ${}_{92}U^{233}$

These constitute two fissile atoms bred in the reactor, against one initially consumed. Thus natural uranium (U^{238}) or Th^{232} serves as a fertile source for breeding fissile atoms.

There are two most common breeding cycles:

i. The Uranium cycle: In this the conversion of fertile U^{238} into fissionable Pu^{238} takes place. The uranium cycle uses high energy neutrons and is carried out in a fast reactor. In these reactors liquid sodium metal or pressurized helium is used as a coolant. No moderator is employed since the neutrons need not be slowed down.

ii. The Thorium cycle: In this the conversion of fertile Th232 into fissionable U^{233} takes place. The thorium cycle is analogous to the uranium cycle. But is works best in a thermal reactor.

Fertile U^{238} is abundant and inexpensive. It constitutes over 99% of naturally occurring uranium. It exists as large stock piles as a by-product of past uranium fuel-enrichment processing.

Fast breeder reactors – Why are they needed?

Uranium keeps disappearing rapidly. The world reserves of uranium are by no means infinite. France, currently the largest producer of nuclear energy, anticipates a near total exhaustion of stocks of uranium in nature by about 2025 AD. It can be taken as a signal by other nations too to look for alternatives to uranium and conserve uranium stocks. World energy reserves can be extended very considerably by the use of Thorium. Natural thorium contains primarily the isotope ^{232}Th. This does not undergo fission with thermal neutron but it has an appreciable neutron absorption cross section to give Th-233, which then decays by beta particle emission through Protactinium to U-233 from a nuclear physics point-of-view, U-233 is the most desirable for use in thermal reactor systems. It is possible to build breeder reactors, for instance of the homogeneous aqueous type, which operate with U-233 fuel in the core and have a surrounding blanket of Th^{232} [7]. Thus there is a need for a fast breeder reactor which not only enables the extraction of 100 times more energy from uranium than via light water reactor (LWR), but manufacturers more fissile material (Pu-239) than it consumes (U-235). After removing the fission fragments, the plutonium isolated can be used as fresh fuel in a second reactor identical to the first.

Operation of Fast breeder reactors in addition to resulting in enormous amounts of energy they yield Pu which is undoubtedly an asset.

Working of a fast breeder reactor:

For the sake of discussion let us consider a specific example of fast breeder reactor, namely the fast breeder test reactor at Kalpak is which is totally designed and fabricated in India. It being fast neutron reactor the fissile content of the fuel should be high in the range of 15-20 percent. Liquid sodium is used as coolant. The power output is 13 MW_e (Megawatt electrical). 70% PuC and 30 % UC in the form of sintered ceramic pellets encapsulated in stainless steel tubes is employed as fuel. Compared to oxide fuel, carbide fuel has higher heating rage and a higher breeding gain.

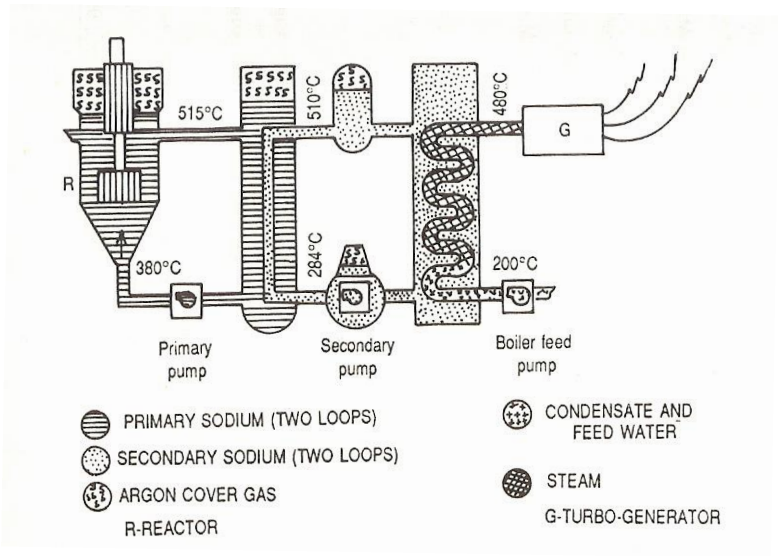


Fig. 3. The Fast Breeder Test Reactor [4]

It being a fast neutron reactor, there is no moderator and hence small size of the reactor core and a resulting much higher power density than in a thermal reactor of same power level. But far more efficient cooling system is needed. A liquid metal with high heat transference and compatible with the fuel and structural material should be circulated along the primary and secondary loops depicted in Fig. 3. In general low melting point metals like ^{7}Li and ^{23}Na were proved to be the best.

A sodium pump drives the liquid metal at 380 ºC into the reactor core from below. When the liquid leaves at the top at 515 ºC much heat would have been extracted from the reactor core. By this time Na^{23} becomes radioactive Na^{24} by (n, γ) reaction. Being radioactive the primary sodium is made to transfer the heat to a sealed second loop of sodium as an intermediate heat exchanger which remains non-radioactive. The two sodium pumps are of special design to keep circulating some 150 tons of molten sodium in the two mutually isolated loops. Thus the activity of the first loop is wholly contained therein. The heat from the secondary sodium loop is finally transferred to a boiler. The steam generated at 480 ºC and 125 kg/cm pressure drives a steam turbine to generate electricity. Thus the breeder reactor generates electricity.

Doubling time: The time needed to set up the second reactor is called the doubling time. In other words, the time required to double the inventory of fissionable material.

Nuclear Fusion:

A thermonuclear reaction in which nuclei of lighter atoms combine to form nuclei of heavier atoms accompanied by the release of large amount of energy is called a fusion reaction.

The Sun – Is the sun truly an inexhaustible source of energy? How?
Can there be an artificial sun?

Truly the light is sweet, and a pleasant thing it is for the eyes to behold the Sun: ***The Holy Bible (Ecclesiastes 11:7)***

Fusion reactions are considered to be responsible for the endless (currently assumed) source of energy given out by the sun.

The sun keeps replenishing its energy because it is continuously supplied with atomic energy from nuclear reactions going on in the interior, where the temperature is of the order of 20 million degrees centigrade. The energy of the sun is supposed to arise from the following thermo-nuclear reactions:

$_1H^1 + {_1H^1} \rightarrow {_1H^2} + e+ + \text{Energy}$

$_1H^2 + {_1H^1} \rightarrow {_2He^3} + \text{Energy}$

$_2He^3$ + $_2He^3$ $\rightarrow$ $_2He^4$ + 2 $_1H^1$ + Energy

The net result of this reaction is the combination of four protons to produce one nucleus of helium $_2He^4$ as represented below:

4 $_1H^1$ $\rightarrow$	$_2He^4$ +	2 $_{+}e^0$
4 x 1.008144	4.003873	2 x 0.000558 = 0.001116
4.032576	4.004989	

Mass loss, Δm = 4.032576 – 4.004989

= 0.027587 amu

Energy released = 0.027587 x 931 MeV = 26.7 MeV

Controlled nuclear fusion:

In sharp contrast to fission, nuclear fusion process could not be controlled. The estimated amounts of deuterium in the water of the earth are 10^{17} pounds (1 kg = 2.2 pounds). Each pound of deuterium is equivalent to 2500 tons of coal in energy. So a controlled fusion reactor would provide a virtually inexhaustible supply of energy. Thus a great effort is being made to build such a reactor. Success in this direction is not too far [8].

Obstacles in exploiting fusion energy:

i. Fuel: Attempts should be intensified to separate deuterium from ordinary water. Production of tritium can also be attempted.
ii. The particles must be heated to temperatures ranging from 50 to 100 million degrees depending upon the particular reaction.
iii. The state of plasma must be present for a long enough time so as to allow a substantial portion of the nuclei present in it to undergo fission.
iv. Technology to harness the released energy to generate useful power also needs to mature.

The energy released is 26.7 MeV for four protons. The heat produced in these thermonuclear reactions makes up the loss of heat by sun’s radiation there by keeping the sun’s temperature constant.

Fusion reactions are used to make hydrogen bomb (thermonuclear bomb). The technology of fusion bombs is different from that of fission bombs (atom bomb). Since very high temperature is required to initiate the fusion reaction of the type $_1H^2$ + $_1H^2$ $\rightarrow$ $_2He^4$, an atomic bomb is used as a trigger [9].

Radio isotopes for Electricity:

Exploiting nuclear reactions such as Fission and Fusion are well heard. But since there is wide scope for the synthesis of new radioisotopes and also enormous number of radioisotopes have already been reported and also large amount of energy is released during the decay of the radioactive atom, attempts can be intensified to develop devices, at least auxiliary power sources, (since the quantum of energy output is orders of magnitude lower than that derived from Fission and Fusion reactions) based on radioisotopes. An interesting example of power generation by using ^{90}Sr radioisotope is presented below:

The Strontium-Ninety Auxiliary Power (SNAP) developed in US is an efficient but auxiliary power source for charging batteries used in submarines, space craft, and unmanned Arctic stations and in nuclear devices coupled to high frequency transmitters for continuous signaling of weather conditions. The 0.54 MeV β emitter 90Sr in the form of strontium titanate ($^{90}SrTiO_3$) is used in the device depicted in Fig. 4. The radioactive source is in a highly compact packing. The packing gets heated to temperatures of the order of 500 ºC. The device provides thermoelectric power through a large number of efficient thermo junctions. The cold junctions outside remain at temperatures around 50 ºC. ^{238}Pu (with half-life 87.7 year period) which is and α emitter with energy 5.4 MeV can also be used in place of ^{90}Sr.

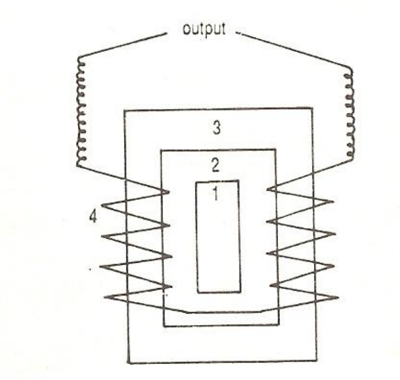


Fig. 4. Radioisotope ($^{90}SrTiO_3$) as a source of thermoelectricity
(Strontium-Ninety Auxiliary Power) [4]
1 – Column of $^{90}SrTiO_3$, 2-Insulator, 3-Shielding, 4-Thermocouples

Such devices are not risk free for enough care need to be taken such that no leak of encapsulation takes place.

Conclusion:

The work of construction should not stop for fear of destruction. Let us go ahead with the option of nuclear energy since the benefits and comforts derived there from out weight the frustrations and fears of peril.

Wisdom is better than weapon of war: but one sinner destroyeth much good.

The Holy Bible (Ecclesiastes 9:18)

References:

1. B. Viswanathan, Editor, Chapter 4, Energy Sources – A Chemist's Perspective, 2006, ebook available on www.nccr.iitm.ac.in.
2. http://forums.delphiforums.com/catalysisindia
3. R. K. Pachauri, Journal of the Petrotech Society, IV (1), 2007, 8
4. H. J. Arnikar, Essentials of Nuclear Chemistry, New age international (P) limited, 1995.
5. Marion L. Shepard, Jack B. Chaddock, Franklin H. Cocks, Charles M. Harman, Introduction to Energy Technology, Ann Arbor Science, Publishers Inc, 1976.
6. Raymond I. Murray, Nuclear Energy, Pergamon unified engineering series, Pergamon Press Inc., 1975
7. J. K. Dawson and G. Long, Chemistry of Nuclear Power
8. O. P. Agarwal, Unified Course in Chemistry, Volume III, Jai Prakash Nath & Co. 1990.
9. C. N. R. Rao, Editor, University General Chemistry, Macmillan