THE ENERGY STORY: FOSSIL FUELS TO NUCLEAR POWER

HISTORIA DE LA ENERGÍA: DESDE LOS COMBUSTIBLES FÓSILES A LA ENERGÍA NUCLEAR

Neelima G. Kelkar

Departamento de Física, Universidad de los Andes, Cra 1E, 18A-10, Bogota, Colombia

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Abstract

The ability to harness energy is a basic requisite for the existence of any civilization. Energy makes things happen. The story of energy essentially is the story of the progress of mankind. We have come a long way since the days our ancestors discovered fire. The explosion of technological advances has however taken place in a rather short time span of about 200 years as compared to the hundred thousand years of the use of fire. The industrial revolution and all the scientific progress happened only after we discovered and started tapping the fossil fuel resources. Unfortunately, this rapid progress has also been accompanied by a rapid population growth. The fossil fuels which were formed millions of years ago will not last forever and it is time to enhance alternative forms of energy production. In the present article we shall discuss this need for alternatives and consider one of the strongest candidate, namely, the nuclear energy option.

Keywords: Alternative energy, Nuclear Energy.

Neelima G. Kelkar: nkelkar@uniandes.edu.co

Resumen

La habilidad para manipular la energía ha sido vital para la existencia de las civilizaciones: la energía hace que las cosas sucedan. La historia de la energía es la historia del progreso de la mente humana. Somos el cúlmen de un proceso que comenzó con el descubrimiento del fuego, pero cuyos avances tecnológicos se consolidaron sólo hace 200 años, siendo fundamental el descubrimiento de las fuentes fósiles. Los combustibles fósiles no son inagotables, por lo cual es imperante pensar en energías alternativas. En este artículo se discutirá la energía nuclear como una de las mejores opciones de las energías alternativas.

Palabras clave: Energía alternativa, Energía Nuclear.

Evolution of Energy Sources.

Since the beginning of energy consumption by humans up to the industrial revolution (18th century), mankind's use of energy mainly relied on biomass sources. Other sources of energy, such as windmills and watermills were present but their overall contribution was marginal. Water wheels were used by the Romans around 30 B.C. and the Chinese were using them for iron casting. In the Middle Ages, the miners started using water wheels to pump water from the mines, grind ore and operate hammers at the metal-smith's forge. Ancient people also used oil, however, not exactly in the form and quantities used now. Prior to the 1800s, light was provided by torches, candles made from tallow, and lamps which burned oils rendered from animal fat. Whale oil was used in lamps and as candle wax. Because it burned with less odor and smoke than most fuels, whale oil, particularly oil from the nose of the sperm whale, became popular and a thriving whaling industry developed to provide oil for lighting as well as a lubricant for machine parts of trains. At the height of the industry in 1856, sperm oil sold for $1.77 a gallon, and the United States was producing 4 to 5 million gallons of spermaceti and 6 to 10 million gallons of train oil annually. If petroleum products, such as kerosene and machine oil,

had not appeared in the 1850s as alternatives to whale oil, many species of whales would have disappeared long ago [1].
By the mid 19th century, the industrial revolution brought a major shift in energy sources with the usage of coal, mainly for steam engines, but increasingly for power plants. As the 20th century began, the major reliance was on coal, but a gradual shift towards higher energy content sources like oil began. This second major shift inaugurated the era of the internal combustion engine and of oil-powered ships. The age of the fossil fuels had begun with the world becoming dependent on coal, petroleum and natural gas for daily needs of cooking, transport and electricity.

End of the Age of Fossil Fuels.

Carbon, petroleum and natural gas were formed many hundreds of millions of years ago before the time of the dinosaurs; hence the name fossil fuels. The age when the majority of them were formed is called the Carboniferous Period which occurred from about 360 to 286 million years ago. At the time, the land was covered with swamps filled with huge trees (30 metres high), ferns and other large leafy plants. The Carboniferous is famed for having the highest atmospheric oxygen levels the Earth has ever experienced and for the evolution of the first reptiles. As the trees and plants died, they sank to the bottom of the swamps of oceans. They formed layers of a spongy material called peat. Over many hundreds of years, the peat was covered by sand and clay and other minerals, which turned into a type of rock called sedimentary. More and more rock piled on top of more rock, and it weighed more and more. It began to press down on the peat. The peat was squeezed until the water came out of it and eventually, over millions of years, it turned into coal, oil or petroleum, and natural gas.
Strictly speaking, coal, gas and petroleum are renewable resources. However they take millions of years to form and we are consuming them very fast. The obvious question which one must then worry

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[1] Despite the extinction of American whaling, the whales were not yet safe. The whaling mantle passed to other countries, notably Norway [1], Japan (for food), and the Soviet Union (for animal fodder and fertilizers).

about is how long will they last? A statistical review of world energy is published every two years by British Petroleum [2]. Apart from the energy production and consumption country wise, these reviews publish the reserve to production (R/P) ratio, i.e., the ratio of the amount of known resource to the amount used per year. The R/P ratio basically tells the remaining amount of resource expressed in time if the production continues as at a given point of time. The R/P ratios according to the latest reviews are 53.3, 55 and 113 years respectively for oil, gas and coal. Some of the optimistic calculations predict that the global decline in oil production distribution would start around 2020 [3]. All this hints toward the end of the age of fossil fuels and the beginning of energy shortages. The speedy consumption of the fossil fuels over the past 200 years has also raised concerns regarding the green house gas emissions and there exist fears [4] that when we have used up all the coal and oil, the earth's climate may have reached a truly life threatening state. There exist opponents to this school of thoughts and we refer the reader to [5, 6] for alternative ideas.

Nuclear Energy Alternative.

Among all the existing alternatives to fossil fuels, nuclear energy is the most powerful one [7]. There are more than 430 commercial nuclear plants in 31 countries with over 370,000 MWe [2] of total capacity (see http://www.world-nuclear.org/ for more information). They provide 11 % of the world's electricity. Unfortunately, there is often a tendency to lump nuclear energy with nuclear weapons and if not that, with something that is absolutely dangerous (understandably, due to the history of accidents at nuclear reactors). It is however important to realize that the power of nuclear energy lies in dimensions. Nuclear energy comes in two flavours: fission and fusion power. In both cases, the nuclear energy available per atom is roughly one million times bigger than the chemical energy per atom of typical fuels.

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[2] Megawatt electrical (MWe) is a term that refers to electrical power output. This could be much less than the thermal (heat) power output of the reactor due to the inefficiency of the steam-turbine generator and other factors.

The amount of natural uranium required to provide the same amount of energy as 16 kg of fossil fuels, in a standard fission reactor, is 2 grams; and the resulting waste weighs one quarter of a gram. To deliver 2 grams of uranium per day, the miners at the uranium mine would have to deal with perhaps 200 g of ore per day. So the material streams flowing into and out of nuclear reactors are small, relative to fossil-fuel streams. However, the fact that the nuclear waste stream is small does not mean that it is not a problem [8]. Indeed it needs to be handled very carefully.

Energy from fission

The energy released in fission is the binding energy of the nucleus. When fission occurs (be it spontaneous or induced by particles), the heavy parent nucleus is split into daughter nuclei with a higher binding energy per nucleon. It becomes evident from the nuclear binding energy curve (which increases rapidly for light elements until it reaches about 8 MeV/nucleon around $A = 56$ beyond which it decreases very gradually) that elements heavier than iron can yield energy by nuclear fission. Thus to gain energy from the process of fusion, one would have to fuse the nuclei lighter than iron. As an example let us estimate the energy released in the neutron induced fission of ^{235}U. If we subtract the masses of the fission product nuclei and the neutrons from the parent uranium in the reaction $n + {}^{235}U \to {}^{236}U \to {}^{141}Ba + {}^{92}Kr + 3n$, the energy released can be seen to be 200 MeV or 3.2×10^{-11} Joules. The energy produced by 1 kg of uranium is then $3.2 \times 10^{-11}J \times 1000$ g $\times$ (1 mol/ 235 g) $\times\ 6.023 \times 10^{23}$/mol $= 8.2 \times 10^{13}$ Joules. This is a large amount of energy and is equivalent to burning tons of coal or oil. The neutrons released in the fission process can further interact with other uranium nuclei and build up a chain reaction. Since the first explanations of the fission process as a “new type of reaction” in 1939 by Meitner and Frisch [9] and Bohr and Wheeler’s theoretical work describing it on the basis of the liquid drop model, the understanding of this complex nuclear process has not ceased to interest both experimental and theoretical nuclear physicists until now [10]. To describe the whole fission process, i.e., properties of the fissioning system, fission dynamics and fission fragment distributions, has been a major challenge in theoretical nuclear physics. The experimental counterpart is equally difficult (for a recent review see [11] and references therein).

Even if the amount of energy produced in nuclear fission is enormous, as mentioned earlier, this sort of energy is clouded by fears due to accidents such as those at Chernobyl, Three Mile Islands and Fukushima. Besides this, there remains the problem of getting rid of nuclear wastes [12]. Depending on the type of waste there exist various methods of managing these wastes. The most long-lived wastes like those from spent fuel are stored in deep geological repositories. Another technique to store the waste which has already been in a spent fuel pool for sometime is the dry cask storage. These are leak tight steel cylinders where the fuel rods inside are surrounded by inert gases. Ocean floor disposal is another way of isolating nuclear wastes in regions where geological or human activity is unlikely. The transmutation of long-lived radioactive waste by accelerator-driven systems (ADS) can be yet another solution [13]. One could consider the thorium alternative (to be discussed below) as a possible alternative, however, one should remember that nuclear wastes are not necessarily more difficult to handle as compared to other industrial wastes [14].

The Thorium Alternative

It is being speculated that thorium (named after the Norse god of thunder), may provide a safer alternative as a fuel. The difference between thorium and other nuclear fuels is that it cannot sustain a chain reaction on its own like for example uranium-233 and plutonium-239. ^{232}Th has a higher neutron yield than ^{233}U or ^{239}Pu per neutron absorbed. Thorium is also estimated to be three to four times more plentiful than uranium in the Earth's crust. It exists in nature in a single isotopic form ^{232}Th which decays very slowly (half life of 14.5 billion years). Recognizing the importance of thorium resources, the International Atomic Energy Agency (IAEA) has in 2010 initiated the activity to compile data on thorium deposits, occurrences and resources and make it available in an online information system at http://infcis.iaea.org/THDEPO/About.cshtml. The present estimate of the resources world-wide is at 6.55 million tones. Thorium is considered a safer alternative since the radioactive waste produced by a reactor running on thorium lasts 10 to 10,000 times less amount of time than the waste from traditional uranium reactors. Besides that, it cannot sustain a chain nuclear reaction like the one at Fukushima. Once the process of adding neutrons is cut off, nothing can happen.

In the thorium cycle, fuel is formed when ^{232}Th captures a neutron (whether in a fast reactor or thermal reactor) to become ^{233}Th. This normally emits an electron and an anti-neutrino by beta decay to become ^{233}Pa. This nucleus undergoes another beta decay to become ^{233}U which can be used as fuel.

$$n +^{232} \mathrm{Th} \rightarrow^{233} \mathrm{Th}(t_{1/2} = 22\,\mathrm{mins})$$

$$\rightarrow^{233} \mathrm{Pa}(t_{1/2} = 27\,\mathrm{days}) + e^- + \bar{\nu}_e \rightarrow^{233} \mathrm{U} + e^- + \bar{\nu}_e$$

^{233}U captures a neutron and fissions generating 198 MeV of energy. Considering the potential of thorium reactors, the use of thorium-based fuel cycles has been studied for about 30 years, but on a much smaller scale than uranium or uranium/plutonium cycles. Basic research and development has been conducted in Germany, India, Japan, Russia, the UK and the USA [7]. Some of the first experiments were carried out between 1967 and 1988 in Germany. The reactor was a small pebble bed reactor that operated at 15 MWe. About 1360 kg of thorium was used in some 100,000 pebbles. The feasibility of using thorium fuels in a pressurized water reactor (PWR) was studied in considerable detail during a collaborative project between Germany and Brazil in the 1980s. A 40 MWe thorium fuelled demonstration reactor also ran in the U.S.A. between 1967 -74. India has made utilization of thorium for large-scale energy production a major goal in its nuclear power programme. In 1995, Kakrapar-1 in India achieved about 300 days of full power operation and Kakrapar-2 about 100 days utilizing thorium fuel. The use of thorium-based fuel is planned in Kaiga-1 and -2 and Rajasthan-3 and -4 reactors. The IAEA has been regularly publishing reports on the developments related to the thorium alternative which can be found in [15].

Recently, a private Norwegian company, Thor Energy, began to produce power at its Halden test reactor in Norway using thorium (http://www.thorenergy.no/).

Fusion Power

The energy released in nuclear fusion per kg of fuel can be bigger than that released in fission and enormous as compared to fossil fuels. Typical reactions that can be considered involve the light nuclei like deuteron (d), triton (^{3}H), helium (^{3}He) or alpha (^{4}He). These reactions and the energy released in their fusion (which can be calculated by the difference of the initial and final masses) are:

$$d + d \rightarrow {}^3\mathrm{H} + p + 4\,\mathrm{MeV}$$

$$d + d \rightarrow {}^3\mathrm{He} + n + 3.3\,\mathrm{MeV}$$

$$d + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + n + 17.6\,\mathrm{MeV}$$

$$d + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p + 18.3\,\mathrm{MeV}$$

A substantial Coulomb barrier must however be overcome for the fusion to happen. For the deuterium - tritium fusion reaction, for example, the energy necessary to overcome the Coulomb barrier is 0.1 MeV. Converting the units between electron Volts and Kelvin shows that the barrier would be overcome at a temperature in excess of 120 million Kelvins. Such barriers can be overcome only in stars. To produce this “star fire” on earth requires highly advanced techniques. The energy produced from fusion should be more than the energy spent in producing the plasma (the hot gas of charged particles) and there has to be also a means to confine the plasma. The International Thermonuclear Experimental Reactor (ITER) is an ambitious project (www.iter.org) which is currently building the world’s largest and most advanced experimental tokamak (device that uses magnetic fields to contain and control the hot plasma) nuclear fusion reactor at Cadarache in the south of France. The project is funded and run by seven member entities - the European Union (EU), India, Japan, China, Russia, South Korea and the United States. At a cost of around 20 billion dollars, ITER is the costliest on going scientific project.

Inertial Confinement fusion (ICF) is another technique used to confine the plasma. There exists a criterion to ensure that the fusion reactions release more energy than is required to produce the hot dense plasma. Let us assume that the plasma consists of deuterons and tritons of density $n/2$ each, that v is the relative velocity of the two nuclei (velocities are Maxwell-Boltzmann distributed) and σ the fusion cross section. The energy produced per time τ depends on the kinetic energy Q of the reaction products and the rate of fusion processes (which can be expressed in terms of the density n and the average value of the product $v\sigma$). It can be shown that [16] only if

$$n\tau > \frac{12 k_B T}{\langle v\sigma \rangle Q}$$

the fusion reactions can produce more energy than is required to produce the plasma at such a temperature and density. This is known as the Lawson criterion and is a fundamental relation for confinement fusion. The difference between magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) can now be understood in terms of this relation. MCF tries to confine the plasma at low densities ($\sim 10^{14}$ to 10^{15} cm^{-3}) for a relatively long time of several seconds whereas ICF tries to achieve extremely high densities ($> 10^{25}$ per cm^3) for a very short time. ICF involves compressing a small amount of fusionable material to very high densities and temperatures by applying strong external forces such as lasers. The National Ignition Facility (NIF) at the Lawrence Livermore National laboratory (LLNL), Livermore, California, is the largest and most energetic ICF device built to date. Based on the technology advances made at NIF, the scientific groups at LLNL wish to proceed with a fusion energy program called LIFE (Laser Inertial Fusion Energy). More details regarding this program can be found at (https://life.llnl.gov/).

How does the story end?

Apart from the nuclear energy option discussed here, there is of course a huge amount of investment being made in other cleaner than fossil fuel and renewable options. Concentrated solar power using gigantic mirrors to focus solar rays on solar towers, off shore wind farms, tidal and wave energy are some such examples. Nuclear energy (from fission) still provides a huge part of the energy needs of the world (for detailed country wise listings, see http://www.iaea.org/PRIS/). Given the safety concerns and the environmental damage that the accidents or mishandling of nuclear waste can cause, it does not however seem to be the most favorable option. Countries like Germany are closing down nuclear reactors and shifting to solar and wind energy options. Considering the ever growing world population which is around 7.2 billion at the moment, it may however not be wise to shut down all nuclear reactors unless we have another equally powerful option at hand.

Population growth, demands for better energy sources and new technologies, and energy consumption are three factors which are inter-related in a complex way. If we do not manage to maintain the right balance, we submit ourselves to the danger of sliding towards a post industrial stone age as described by the Olduvai theory [17]. The fossil fuel (conventional as well as the difficult to extract and so far unexplored) resources will end one day. The energy story which took a big turn with the discovery of fossil fuels though, will most likely not end. If it does, it surely will not be a happy ending. Let us hope then that with cleaner energy alternatives and a wiser management of the resources, the generations to follow keep the story going.

This hope is somewhat justified if we recall the short-short story of mankind [18] where Steinbeck mentioned that when faced with problems, right from the cave days, mankind has never chosen extinction. “If we do, we’re stupider than the cave people and I don’t think we are. I think we’re just exactly as stupid and that’s pretty bright in the long run” [18].

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