# Chapter 1
# Nuclear Energy, Introduction

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In terms of technical progress of the human species/society, the second half of the twentieth century is marked by two developments: the computer and nuclear energy. And the two are related since progress in the development and applications of nuclear energy owes a lot to the power of computations made possible by the digital computer.

The whole twentieth century is marked by the ever-increasing use of electricity. The century started with a tiny amount of electricity use and ended with ~30% of the total energy consumed to be in the form of electricity.

Nuclear energy, unfortunately, was released in the world as a weapon. But, fortunately, after the initial shock of Hiroshima and Nagasaki, nuclear energy turned out to be of great benefit to society. First, in a "Faustian bargain," of sorts, the existence of nuclear weapons resulted in having a *cold war* between the two superpowers of the time (Soviet Union and the USA) instead of a *hot one*. Second, nuclear energy proved to be an excellent method of generating electricity and also provided the means for numerous applications in industry, science, education, and probably most of all medicine. Not even the fiercest critics of nuclear energy deny the benefits of nuclear medicine in correct diagnosis and therapy and, therefore, prolongation of life for millions of people all over the world.

Although, as mentioned above, nuclear energy touches today beneficially many aspects of our lives, the most prominent application is the generation of electricity by using nuclear fission reactors to generate heat that is used to produce steam (or hot gas) that runs a turbo generator and produces electricity. There are many advantages in using nuclear energy for the generation of electricity. Primary among them is the absence of green house gases and other pollutants such as sulfur oxides, nitrogen oxides, heavy metals (mercury etc.).

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Probably, the most important difference between nuclear and fossil or any renewable fuels is the concentrated energy release of the former. The fission of one U nucleus releases ~200 × $10^6$ eV; the burning of one atom/molecule in a chemical reaction releases a few eV; a ratio of many million! A single pellet of nuclear fuel, about the size of a fingertip, contains as much energy as 1,700 $ft^3$ of natural gas, or 1,780 lb of coal, or 149 gal of oil. As a result of this concentrated energy, the "ashes" of the process, the fission products that are radioactive, constitute a, relatively, small volume. Yes, they have to be safeguarded and be kept away from the biosphere for thousands of years, but the volume of wastes is considered manageable.

Today (2011), there are 441 nuclear power plants operating in the world amounting to a total generating capacity of 375 GWe. The top five countries, in terms of number of operating plants are the USA (104), France (58), Japan (54), Russia (32), and Korea (21). In 2010, there were 62 plants under construction amounting to a capacity of 60.2 GWe. The top countries in numbers of plants under construction are China (25), Russia (11), Korea (5), and India (4); two plants under construction are in the USA, Japan, Bulgaria, Slovakia, and Ukraine.

- Today, ~16% of the electricity worldwide is produced by nuclear power plants; that fraction will increase in the coming years as developing economies (e.g., China and India) and developed ones (Korea, Japan, and Europe) complete their announced ambitious nuclear expansion in order to satisfy their ever-increasing demand for electricity. The World Nuclear Association (WNA) projects that by 2060 at least 1,100 GWe of new nuclear capacity will be added.

What drives this "Nuclear Renaissance"? There are several factors:

1. *Increasing energy demand*: Due to an ever-increasing population and desire of the underdeveloped countries to improve their standard of living. In addition, a need for new plants materializes because old plants reach the end of their life and must be shut down (all types of electricity generating plants, not only nuclear, are designed with a finite operational life).
2. *Climate change concerns*: Increased awareness that fossil fuels release a large amount of greenhouse gases that may lead to a planetary climate change are driving decisions for new plants to be "green," that is, to emit reduced amounts of greenhouse gases and other pollutants or not at all. Nuclear power plants are the only ones generating electricity with, essentially, zero emissions.
3. *Economics*: The main cost component of a nuclear plant is its construction cost; once this cost is overcome, the other two cost components for the generation of electricity (O&M and fuel) favor nuclear over fossil plants. Experience during the past 50 years, especially in the USA, has shown that nuclear is the best plant for generation of base load electricity, both in terms of cost and reliability.
4. *Fuel price stability*: Because the fuel cost constitutes a, relatively, small fraction of the total cost of generating electricity (for nuclear the main cost is the construction cost; fuel cost is between 10% and 16% of the total cost), even if the price of fuel doubles, the effect on the cost of electricity will be minimal.

It should be noted that the cost components of the fuel are uranium, conversion, enrichment, fabrication-transportation; of these, only the uranium price fluctuated during the previous 50 years; the cost of the other components has been remarkably stable.

5. *Security of Fuel Supply*: Supply of fossil fuels (oil, gas, and coal) is vulnerable to interruptions of supply due to political turmoil, strikes, weather, etc. On the contrary, uranium is plentiful and available at reasonable prices, for the foreseeable future; more than that, since nuclear plants refuel every 2 years, it is quite likely that short-term upheavals can be settled before they have an effect on nuclear fuel supply.
6. *Nuclear Safety and Public acceptance*: The safety record of nuclear power plants during more than 50 years of operation (195702011) is outstanding. There were three accidents during that period. The TMI accident in the USA in 1979: it was a financial loss to the company operating the plant; not a single injury resulted to any person in or out of the plant and there was no contamination of the environment. The Chernobyl accident in 1986 was a very serious accident: radioactivity was released to the environment and 33 persons are known to have died, mostly firefighters. Some cancers will develop as a result of exposure to the radiation from the accident, making it a difficult task to quantify them. One should note, however, that no plant licensed anywhere today can have the Chernobyl type of accident; it is physically impossible (the Chernobyl design has been abandoned). Considerable area around the plant has been contaminated, but the reports today (2011) indicate that life is returning to normal. On March 11, 2011 a 9.1, Richter scale, earthquake hit Japan and affected the Fukushima nuclear site. There are six reactors on that site. On that day, two reactors were shut down and were not affected by what followed. When the quake hit, the four operating plants shut down, as design dictated. Shutting down means that the fission reaction is stopped; however, heat continues to be generated in the core from fission products, hence cooling must be provided. As per design, cooling continued using emergency diesel generators required by regulation and readily available for such eventuality. Then, 15–20 min later, the tsunami arrived; the waves of the tsunami swept away generators and their fuel supply and cooling of the core was lost. Fuel meltdown of the cores occurred and radioactivity was released to the environment. Two plant workers were killed by the tsunami; these are the only immediate deaths as a result of this event. The tsunami itself and the earthquake resulted in the death of ~22,000 people. The area around the site was contaminated. Definitely the accident was a tremendous financial loss to the company operating the Fukushima plants.

   As a result of the accident at Fukushima, two plant workers were killed by the tsunami; these are the only immediate deaths as a result of this event. At Chernobyl, ~33 persons, mostly firefighters, were the reported immediate deaths. Of course as a result of TMI, no deaths occurred; in fact in the USA there are zero deaths from the operation of commercial nuclear power plants from 1957 until today. Compare this, for example, to coal mining fatalities which amount to ∼30/year in the USA; in other countries, e.g., China, the direct annual death toll from coal mining is much higher.

Without trying to deemphasize the importance of these three accidents, the net effect is that the world community still recognizes and accepts the generation of electricity using nuclear fission reactors as an indispensable component in the energy portfolio. At about 9 months after the Fukushima accident, there is no report of any country changing nuclear energy policy because of that accident (with the exception of Germany that decided to accelerate the shutdown of its nuclear fleet following a decision taken earlier by its Government). Overall acceptance of nuclear technology is the result of its excellent performance; another factor in favor of nuclear power is the lack of greenhouse gases by this technology or of any environmental effect in the vicinity of the plant. In the USA, acceptance of nuclear power by communities around the plant is ∼70% or more favorable.

The nuclear industry, especially in the USA, learned and improved a lot after the TMI accident. I have no doubt that the international nuclear community will apply the lessons learned from Fukushima to make the already safe record of this industry even safer.

This section on Nuclear Energy consists of 19 articles that cover all aspects of the nuclear enterprise. Here is a brief description of each article:

A. *Radiation sources*: It discusses radioactivity and basic radiation sources.
B. *Radiation detection devices*: One characteristic of radioactivity is the fact that it can be detected relatively easily and accurately. This article discusses the devices used to accomplish such measurements.
C. *Dosimetry* and *Health Physics*: Very early in the twentieth century (1920s), it was realized that ionizing radiation may be harmful to humans, therefore measures must be taken to protect people. These measures were based on (a) quantifying the effects of radiation exposure by establishing units of radiation dose and means to measure it and (b) establishing professional bodies that set protection standards [ICRP (1928), NCRP (1964) etc.]. The field of Health Physics was thus born resulting in great benefit for the radiation workers.
D. *Fission reactor physics*: Fission reactors are the major sources of production of radioactive materials. What are the principles of their operation? What are the foundations of their safe operation? These are two of the major items discussed in this article.
E. *Nuclear fuel cycles*: Providing nuclear fuel for a fission reactor is not a simple or straightforward task; it involves many steps (U procurement, conversion, enrichment, fuel rod and assembly fabrication). The users of the fuel are presented with choices, such as discarding the irradiated fuel as waste or reprocessing and recycling it. Also, reactor designers may affect the nuclear fuel "cycle" by building reactors that just produce electricity, or combine electricity production with generation of new fuels (breeders), or generate electricity in combination with burning some of the nasty by-products of the fission process. These are the matters discussed in this article.

F. *Uranium reserves and mining*: How much uranium is there on our planet and at what price? Where is it found? How is it extracted? These are the topics of this article.
G. *Nuclear fission power plants*: Once the fission reactor is designed and ready to operate, how is the fission energy utilized to generate electricity? The reactor core itself is not enough; plenty of other components must operate for the successful transformation of energy released in fission to electricity feeding a lightbulb. The fission reactor core makes a small part of a nuclear power plant. It is this aspect of nuclear power, components and activities outside the core, that is described in this article.
H. *Nuclear reactor materials and fuel*: For a successful and long-term safe operation of a nuclear power plant, the materials used, especially those directly tied to the fuel, must function as designed (as expected) in the very hostile environment of a nuclear fission core. This article describes the pros and cons of the various materials that have been considered and the final choices made.
I. *Nuclear safeguards and proliferation of nuclear weapons materials*: Of great concern to human kind is the acquisition of nuclear materials by groups or governments that may use them to make nuclear weapons, contrary to international treaties. This "proliferation" or rather "nonproliferation" of nuclear materials and possibly weapons is a concern that will never disappear; all that can be done by the international community of nations is to set up treaties, policies, and procedures that diminish the probability of proliferation. It is these aspects of this terrible problem facing humanity that are discussed in this article.
J. *Radiation shielding and protection*: This article is complementary to articles A–C. Having discussed radiation sources, dangers from radiation, and standards of protection, how does one provide the means for a safe radiation environment for the workers and the public? How are relevant computations performed? Measurements? How is an effective radiation shield designed? These are the questions answered in this article.
K. *Isotope separation methods for nuclear fuel*: The two elements found in nature that may be considered as fuels for fission reactors are Th and U. Unfortunately, only certain isotopes of these elements or made with the help of these elements can be manufactured into fuels. Hence, isotope separation methods must be employed for the production/concentration of the "useful isotope(s)." These methods are discussed in this article.
L. *Reprocessing of nuclear fuel*: Irradiated fuel contains many useful isotopes, primarily U and Pu. Reprocessing is the operation that extracts the useful isotopes from the irradiated (spent) fuel. The reprocessing methods used until today and those under research and development are discussed in this article.
M. *Decommissioning of nuclear facilities*: Every nuclear facility has a finite lifetime; at the end, when operations stop for good, the law says that the site must, eventually, be returned to its preoperational state in terms of the presence

of radioactivity. This is what decommissioning means. All the tasks associated with decommissioning are discussed in this article.

N. *Radioactive waste management*: Storage, transport, disposal. The operation of fission reactors results in the production of radioactive materials. Such materials, if they have no further use, they must be safeguarded for long periods of time in order that their release to the biosphere may be prevented. The method of eventual disposal of such materials considered today by their producers is placement in a geologic repository. In the meantime, radioactive wastes must be stored and transported. These activities are discussed in this article.

O. *GEN-IV reactors*: By any measure, current fission reactor designs are successful. However, there is room for improvement in terms of fuel utilization, thermal efficiency, use of the heat generated by the energy released in fission, multifunction of a nuclear plant, etc. There is considerable global effort underway to design fission reactors that will show some, if not all, of the improvements just mentioned. These new designs, collectively named as GEN-IV reactors, are described in this section.

P. *Nuclear fusion*: Fusion reactors offer many advantages over fission reactors. Unfortunately, although fusion became known to man before fission and life on earth owes its existence to a fusion reactor in the sky (our Sun), no fusion plant has been built yet; fusion reactors present some unique challenges/ difficulties that have not been resolved yet. But, the world's scientific community is working as a team in an effort to resolve the issues and build an operational fusion plant sometime in the future. All the past and current efforts in fusion research and the expected future developments are presented in this article.

Q. *Nuclear power economics*: In a free market, every plant generating electricity must compete economically with all other options; nuclear is no exception, of course. Nuclear power presents some unique problems, with respect to financing, and these are the problems (and possible solutions) discussed in this article.

R. *Thorium – An excellent 'fertile' nuclear fuel*: In addition to Uranium, Thorium (Th) is the only other element found on earth that can be used as a fuel in fission reactors. The Th properties, relevant to fission reactors, resources, availability and prices are discussed in this article.