FUDMA Journal of Sciences (FJS)
ISSN Online: 2616-1370
ISSN Print: 2645-2944
Vol. 2 No.3, September, 2018, pp 139 - 145

AN OVERVIEW OF COMPUTATIONAL POTENTIALS IN NIGERIA FOR DESIGNING A NUCLEAR REACTOR SYSTEM FOR RESEARCH OR POWER APPLICATION

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ABSTRACT

Nigeria, with seven nuclear research centers has no technical know-how to develop and operate a nuclear power plant for electrical production, 38 years after the introduction of nuclear program in the country. Our goal in this study is to provide a review of Nigeria's potentials to fabricate a nuclear reactor system for research or power application. Generally, Reactors are first designed and tested on paper before the actual manufacture and the real systems are expected to behave as predicted by reactor physics computer calculations. Countries usually designed new reactor system by studying the success records of other countries, by reviewing its own previous experience, or by the availability of nuclear materials. Nigeria must engage the services of the local scientists to design a reactor system for the development of the country's nuclear power program. Over-dependence on the imported finished products and services has retarded the growth of science and technology in Nigeria. The proposal to acquire four nuclear power plants from a foreign firm without tasking our local scientist to design and develop such facility for Nigeria might not speedup the growth of the country’s nuclear energy program. Nigeria can study the success records of sister countries to develop its own experience on the use of nuclear energy for electrical production. This will have a more positive impact on the growth of the Nigeria nuclear power program as compared to engaging the service of foreign experts to design, construct, operate and decommission a nuclear power plant for electrical production in Nigeria.

Keywords: *Reactor, Design, Power, Plant, Computer, Codes, Electrical, Fission, Energy, Nigeria*

INTRODUCTION

The task of designing and constructing a nuclear reactor system is usually very difficult and complicated because different kinds of materials are available for use in the construction of nuclear reactors. In principle, many combinations of these materials can produce a wide variety of reactor designs. Some of them have basic incompatibilities, but among many that appeared to be practical, there is apparently no best design for a nuclear reactor system (Salawu, 2014). Because every concept that had been proposed have advantages as well as disadvantages. In the early stage of reactor development, countries usually design a new nuclear reactor either by the successful experience of other countries, by its own previous experience, or by the availability of nuclear materials. For example, the present Nigeria Research Reactor (NIRR-1) was constructed by CHINA based on the successful experience of the Canadian SLOWPOKE reactor design (Ahmed *et al*, 2006*).* In addition, the six reactors at the Fukushima Daiichi nuclear power plants in Japan were Boiling Water Reactors (BWR) originally designed by General Electric (GE) of United State of America (Wikipedia, 2015). Therefore, it is extremely important for Nigeria to study very well, the success records of nuclear power programs from different countries to develop its own experience on nuclear energy, before purchasing a nuclear power plant for electricity production. Note that all nuclear reactor systems are generally designed and tested on paper before the actual manufacture and the real systems are expected to behave as predicted by reactor physics computer calculations (Salawu *et al*, 2013). Some of the reactor physics computer codes that are available for use in the design of a nuclear reactor system include MCNP, SCALE, VENTURE PC, WIMS/CITATION and HAMMER/EXTERMINATOR, etc. They were used here in Nigeria to perform a variety of reactor physics computer calculation for the present Nigeria Research Reactor 1, NIRR-1 (see Salawu*et al*, 2013, Balogun, 2003 and Jonah *et al*, 2007). The results obtained from these calculations were in good agreement with experimental results as well as the results from a similar calculation performed by China Institute of Atomic Energy (see FSAR, 2005).

Nigeria Nuclear program

The Nigeria nuclear program was founded in 1976 (John, 2014) and a total of seven nuclear research centers (NERCs) established between 1976 and 2010 (table 1.0). These Centers were created with a mandate to conduct researches, develop and train manpower in nuclear technology, engineering, and sciences (Akusu and Mordi, 2014). With all the nuclear research centers put together, Nigeria has no experience to develop and operate a nuclear power plant for electricity production, 38 years after the introduction of the nuclear program in the country (Chijioke and Svetlana, 2015). In fact, the country is currently negotiating with a Russian firm (in early 2015) to obtain four nuclear power plants for generating 4800MW of electricity at the cost of 80 billion dollars (Premium times, 2015). One of the locations already identified by the Nigeria Atomic Energy Commission (NAEC) for installing one of these expensive nuclear power plants in Nigeria was GEREGU, in Ajaokuta Local Government Area of Kogi state (Emeka, 2015), a distance of about 85km away from Adankolo Campus of Federal University Lokoja. With such level of proximity, the University community could be exposed (directly or indirectly) to any risk associated with the use of a nuclear power plant in its neighborhood. In the event of a nuclear power reactor accident, such exposure may have the ability to distort the day to day operational activities of Federal University Lokoja. Note that people can be evacuated within 80km radius from the site of a seriously damaged nuclear power plant (see ANS, 2012). It is therefore extremely important the communities in the vicinity of nuclear power installation across the world are properly informed about the benefit and the risk of generating electricity from nuclear energy in a country with no experience to develop and operate a nuclear power reactor system. The devastating effects of the 2011 nuclear accident in Japan, that prompted the evacuation of about 160,000 people from the exclusion zones (losing their homes and all their properties) is still very fresh in the mind of so many people within and outside Nigeria. The heavy economic loss of a nuclear meltdown is usually borne by the public and not by the companies that designed, built, and operate a nuclear power reactor (Greenpeace, 2015). The lesson learned from this type of nuclear accident has discouraged many nations (such as Germany and Switzerland, etc) from building new nuclear power plants, with a plan to phase out the existing ones as quickly as possible (Wikipedia, 2015b, and Godswill, 2015). Other countries who returned to the nuclear option based their choice on economics and the effect of greenhouse gas emission associated with the use of Fossil fuels (Godswill, 2015). Our goal in this particular study is to enlighten Nigerians about the basic concepts of nuclear reactor physics with an overview of Nigeria's potential to design locally a nuclear reactor system for research or power application. Having detail computational knowledge of various design parameters, for the safe operation of the proposed nuclear power plants, before introducing them into the country is extremely important. Note that the International Atomic Energy Agency (IAEA) has advised the country (and not the reactor construction company) to prepare to take adequate responsibility for the safety culture and for the safe operation of a nuclear power plant in Nigeria (Emeka, 2015). Factors that contributed to the severity of the 2011 nuclear accident in Japan include human errors, flaws in governance and regulatory oversight (ANS, 2012). These types of errors in the management of a nuclear power reactor could be higher in Nigeria as compared to Japan.

The Benefit of Generating Electricity from Nuclear Energy

Since the discovery of a nuclear reactor system in 1942, there are over 439 nuclear power reactors currently generating electricity in over 30 different countries, with only 4 (France, Belgium, Hungary and Slovakia) using it as the primary source of energy for electricity production (Wikipedia, 2015b). Many developing countries (including Nigeria) are making serious efforts to introduce a nuclear power plant in their country with Iran at the forefront. The nuclear power method is desired because it provides answers to many of the challenges associated with other means of power generation (ANS, 2015).

Table 1: List of Nuclear Energy Research Centers (NERCs) in Nigeria

S/no	Location	Name of Institution	Year of Establishment
1	**South West** (OAU Ife)	Center for energy research and Development (CERD)	1978
2	**South East** (FUT-Owerri)	Center for Nuclear Energy studies and training (CNEST)	2010
3	**South-South**(Univ. of Porthacort)	Center for Nuclear Energy Studies (CNES)	2010
4	**South-South** (Koluama in Bayelsa State)	Marine Contamination Coastal Field Monitoring Station (MCCFMS)	2010
5	**North-West** (ABU Zaria)	Center for Energy Research and Training (CERT)	1978
6	**North-East** (Univ. of Maiduguri)	Center for Nuclear Energy Research and Training (CNERT)	2010
7	**North Central** (SHESTCO Abuja)	Nuclear Technology Center	1988
8	FCT Abuja	NAEC	1976/2006
9	FCT Abuja	NNRA	2001

It resolves problems in the areas of economics, reliability, sustainability, safety, and environment etc (ANS, 2015). It is the most economical forms of energy production method as the nuclear fuel cost represent only a fraction of the cost of fossil fuel. In addition, the cost of operating a nuclear power plant (including capital plus non-fuel operating cost) is almost equal to that of a fossil fuel. The nuclear option provides the cheapest electricity production cost in the world. They are designed to produce a large quantity of power and can maintain operation for about two years without refueling (ANS, 2015). A typical nuclear power plant can supply a large amount of predictable and reliable electricity in any extreme weather condition (i.e. dry or rainy season). They emit no gaseous substances into the atmosphere and therefore contribute nothing to environmental pollution, greenhouse gas effect or acid rain. In addition, employees of nuclear power plant receive a very small radiation exposure typically of workers in all other occupation because the increase in radiation around a nuclear power plant is relatively small as compared to the natural background radiation and it is less than the radioactivity released from a typical coal-fuelled power plant (ANS, 2015). Finally, very little nuclear fuel materials need to be removed from the ground to produce power equivalent to a large number of fossil fuels. Therefore, the environmental impact of mining a nuclear fuel is very much less as compared with mining and drilling for fossil fuels (ANS, 2015).

The Risk of Generating Electricity from Nuclear Energy

Nuclear power plants are generally designed to be safe and are operated without any significant effect on public health, safety and environment (USNRC, 2011). But the fission products released in fission reactions during reactor operation are very radioactive. These radioactive materials are contained within the reactor by several barriers including fuel cladding, heavy steel reactor vessel, the primary cooling water system piping and the containment building made of a heavily reinforced structure of concrete and steel (USNRC, 2011). The only ways one can be exposed to radiation from a nuclear power plant is mainly through small releases during routine plant operation, accidents in the nuclear power plant, accidents in transporting radioactive materials and escape of radioactive wastes from confinements systems (Bernard, 2015**)**. Therefore the major risk associated with the use of nuclear power plants arise from these accidental releases of radioactive materials (i.e. radiations) into the reactor surrounding environment. These radiations can penetrate deep into the human body, damaging biological cells and initiate cancer disease or cause genetic diseases in progeny if they strike sex cell (Bernard, 2015). In the United State of America with over 100 operating nuclear power plants, the nuclear power radiation exposure of an average American is about 0.2% of his exposure from natural radiation (which is estimated to cause about 1% of all cancers). Hence radiations due to nuclear technology increase the cancer risk of an average Americans by 0.002% and reduce the life expectancy by less than one hour. Whereas the loss of life expectancy from other competitive electricity generation technologies like the burning of coal, oil, or gas, is estimated to range from 72 hours to 960 hours (Bernard, 2015). A very high radiation dose can destroy body functions and lead to death within 60 days (Bernard, 2015), but such a level of radiation exposure is very uncommon in reactor meltdown accidents. The three major reactor accidents in the 50-year history of civil nuclear power application are the Three Mile Island in the USA (1979), the Chernobyl in Ukrain (1986) and Fukushima in Japan (2011). Apart from the Chernobyl accident, no single death was ever recorded as a result of radiation exposure due to a commercial nuclear reactor incident. In the Chernobyl incident, the destruction of the reactor by steam explosion and fire killed 31 people (which later rise to about 56) with a significant health and environmental consequences (WNA, 2015).

Designing a Nuclear Reactor System

Uranium and Thorium are the two basic materials that can be used as fuel in a nuclear reactor. But uranium is presently the most common reactor fuel material and almost all nuclear reactors use it as fuel in the reactor core. The ore of natural uranium contains a very low concentration of U235 (0.72%) which can undergo fission very easily than the much abundant U238 (99.27%) in the ore (USNRC, 2015). As part of the process of preparing natural uranium for use as fuel in the reactor core, the number of U235 atoms in relation to U238 atoms in the ore is usually increased to about 3.5% or higher and then fabricated into ceramic pellets. These pellets are loaded into metal tubes, made of aluminum or zirconium alloys and pressurized with helium gas when the tube is filled (USNRC, 2015). Plugs are installed on the fill tube and welded to produce the fuel rod (USNRC, 2015). The fuel rods are bundled together into fuel assemblies or fuel elements for installation into the reactor vessel at the nuclear power plant. Alternatively, the enriched uranium can be fabricated into ceramic plates, which are also bundled together to produce a plate type fuel assembly. In other types of reactor design like MNSR or SLOWPOKE reactor, the fuel rods or pins are arranged in concentric circles. The core of a typical nuclear reactor contains the fuel rods or fuel assemblies, the moderator, coolant, and reflector. While the fuel is responsible for the release of fission energy and the criticality of the reactor, the moderator is used to slow down energetic neutrons to thermal energies. Light water, Heavy water, Graphite (the common form of carbon), Beryllium and Beryllium oxide can be used as a moderator in the design of a nuclear reactor (Lamarsh and Baratta, 2001). The coolant is generally used to remove heat from the reactor. Examples of materials commonly used as a coolant in nuclear reactors include light water, heavy water, gases and liquid sodium. Another important component of a nuclear reactor is called a reflector that is made of moderating material surrounding the reactor core and is used mainly to return into the core some of the neutrons that will have escaped from a bare core. A rod of neutron absorbing material is generally used as the control rod in the reactor system. Since this material eats up neutrons (i.e. absorb neutrons), a withdrawal of the rod increases the neutron population whereas insertion decreases it (Lamarsh and Baratta, 2001). Therefore the reactor can be started up, shut down and the power output can be changed by the movement of the rods. The control rods are also used to maintain criticality and operation at a specified power level. Examples of material that are used to manufacture control rods for nuclear reactors include Boron steal, hafnium, and cadmium etc (Lamarsh and Baratta, 2001). Note that SLOWPOKE reactor design is very much identical with the design of the Nigeria Research Reactor-1, a Miniature Neutron Source Reactor (MNSR) manufactured by China Institute of Atomic Energy (CIAE).

A review of the design style of the Nigeria Research Reactor - 1 (NIRR-1)

The Nigeria Research Reactor 1 (NIRR-1) is located at the Centre for Energy Research and Training (CERT) of Ahmadu Bello University Zaria and has been working safely since 2004 till date (Salawu *et al*, 2015). There are about 347 active fuel rods in the core of NIRR-1, arranged in 10 concentric circles. Light water is used as a coolant as well as moderator while metallic beryllium, surrounding the fuel rods, is used as a reflector. The arrangement of these materials in the core of NIRR-1 is similar to that of a SLOWPOKE reactor. The NIRR-1 core assembly is located at the bottom of the reactor vessel, suspended from the "I" beam structure that is embedded into the reactor pool wall. Just like the SLOWPOKE reactor, NIRR-1 has only one central control rod which performs the functions of safe startup, shutdown, power regulation and control of reactivity (Jonah et al, 2007). The fuel rod of NIRR-1 is produced with 90.2% $UAl_4 - Al$ material and the cladding is an aluminum alloy. The heat produced in the reactor core is removed primarily by natural convection/water recirculation (Ahmed et al, 2006) and is transferred to the pool water that serves as the heat sink.

Since 2004 till date, Nigeria has made a lot of significant progress in the field of computational reactor physics studies and reactor design calculation from various research activities at the Center for Energy Research and Training of Ahmadu Bello University Zaria-Nigeria. A number of reactor Physics computer codes have already been used here in Nigeria to perform a repeat design calculation for the present NIRR-1 system as well as designing a model for the core conversion studies of the system from High Enriched Uranium to Low Enriched Uranium fuel. The results from these calculations were in excellent agreement with experimental results as well as the results of similar calculations performed by China Institute of Atomic Energy, the designer of NIRR-1 or by Argon National Laboratory in the United State of America. The most comprehensive ones among these reactor physics calculations, carried out here in Nigeria, include the work of Prof. Balogun of 2003 (Balogun, 2003), Prof. Jonah of 2007 (Jonah et al, 2007) and Dr. Salawu's work of 2013 (See Salawu, 2013). This level of progress in the field of nuclear reactor physics design calculations is sufficient for Nigeria to initiate the process of designing locally a nuclear research reactor with a simple design (like the present NIRR-1) for research purposes before graduating to the design of a complicated power reactor for electricity production.

Large Scale Electricity Production

There are several ways of generating electricity in the world and the use of an electrical generator is by far the most successful for large-scale electrical production and distribution (USNRC, 2015). All electrical generators consist of a magnet (the rotor) which revolves inside a coil of wire (the stator) to create a flow of electrons (the electricity) in the wire. The driving force for the rotor can be provided by a mechanical device in the form of a steam turbine, water turbine, wind turbine and diesel engine etc. The turbine is connected to the electrical generator and the kinetic energy (i.e. energy due to motion) of the steam, water (falling under gravity) or wind pushes against the fan type blades of the turbine, causing the turbine as well as the attached rotor of the electrical generator to rotate and produce electricity (USNRC, 2015). In a typical hydroelectric power plant, the blade of the water turbine rotates, whenever water flowing from higher level to lower level travels through it, causing the rotor of the attached electrical generator to spin and produce electricity. A wind turbine converts kinetic energy from the wind into electrical power. The energy in the wind turns the blades of the turbine around a rotor, connected to the main shaft that spins a generator to create electricity (DOE, 2015). But in a fossil-fuelled power plant, heat from the burning of coal, oil, or natural gas is used to boil water for the purpose of producing steam that is piped towards the blade of the steam turbine. This steam rotates the blade of the turbine and then turns the rotor of the attached electrical generator to produce electricity. Many of the components in a nuclear power plant are very much identical to a fossil-fuelled power plant except that, the steam boiler is replaced by nuclear steam supply system that consists of a nuclear reactor and all other component used in the production of high-pressure steam for the turbine driven electrical generator (USNRC, 2015). The thermal energy (i.e. heat) use in the boiling of water to produce steam in a nuclear power plant does not come from the burning of fossil fuel, but from the fissioning (i.e. splitting) of fuel atom (e.g. Uranium atom) in the core of a nuclear power reactor (USNRC, 2015).

Basic Concepts of Nuclear Reactor Physics

All nuclear reactor systems are designed to maintain chain reactions, producing neutrons and energy (in the form of heat) by the fission of heavy nuclei such as uranium or thorium. The thermal energy released from fission reactions in a nuclear reactor can be used to boil water for the purpose of producing steam for electricity generation using a steam turbine driven electrical generator. The released neutrons in the reactor core can be used for multiple purposes including testing of materials, conducting basic research, and the production of radiopharmaceuticals for medical diagnosis and therapy (ENS, 2015).

Many of the problems associated with the use of nuclear energy are caused by the radioactivity of the fission products and its associated decay heat (White, 2011). The radioactive fission product must be contained, cooled after shutdown and stored as waste after removal from the reactor system. About 92% of the total recoverable energy per fissions goes away very quickly after the reactor is shutdown. But the remaining 7-8 percent of this energy, which is due to fission product decays, does not vanish immediately and it represents a significant contribution of energy in a reactor for a long time after shutdown (White, 2011). Therefore cooling is required for a long period of time in a reactor system even when the reactor is not in operation (Lamarsh and Bratta, 2001). If this cooling is not supplied to a reactor in a shutdown mode, the temperature of the fuel material may increase to a level where the integrity of the fuel can be compromised and the fission products may be released to the reactor surrounding environment (Lamarsh and Bratta, 2001). The loss of cooling water to the power reactor (that is in a shutdown mode) due to the effect of Earthquake/Tsunami in Japan was the major cause of the nuclear accident at the Fukushima Daiichi Nuclear Power plant in 2011 (Wikipedia, 2015a).

One of the important parameters that must be calculated in the design of any nuclear reactor system is called the neutron Multiplication Factor (k), used to describe the neutron balance in a nuclear reactor system. The reactors are controlled by manipulating the neutron economy such that, on the average, only one neutron produced in each fission reaction produced another fission reaction. When this condition is satisfied exactly, the reactor is said to be critical (White, 2011). Thus the effective multiplication factor is a measure of criticality and an indication of how the fission chain reaction is proceeding. Equation 1.1 (which is called balance equation) is an extremely important equation in all fields of Physics and Engineering. This equation states that the rate of change of the quantity of interest is equal to the production rate minus the loss rate.

$$The\ rate\ of\ chang = Production\ Rate - \ Loss\ Rate \quad 1.1$$

In reactor neutronic calculation, the quantity of interest is the neutron population within the reactor. When the neutron production rate and loss rate are in balance, then the neutron population remains constant or in steady state, we have

$$The\ rate\ of\ change$$

$$= Production\ Rate - Loss\ Rate\ = 0 \qquad 1$$

The neutron multiplication factor k is obtained by dividing equation 1.2 by the loss rate. i.e.:

$$k = \frac{Production}{Loss} \qquad 2$$

The three major neutron sources in a nuclear reactor include external source, fission source and in scatter source while the three-loss term includes leakage, absorption and out scatter (White, 2011). The reactor is said to be **critical** if the neutron production rate is equal to the loss rate and k has a value of one (i.e. $k = 1$). For a **supercritical** reactor, production is greater than the loss (i.e. absorption + leakage) and k has a value greater than one (i.e. $k > 1$). The value of k is less than one (i.e. $k < 1$) in a **subcritical** reactor where production is less than the loss (i.e. absorption + leakage).

The **reactor power** can be increased or decreased by regulating the absorption rate through the movement of control rods, made of materials with a relatively high ability to absorb neutrons. From the steady state, removing the control rod will decrease the absorption term and causes the production to be greater than the loss ($k > 1$). Therefore the neutron population begins to increase with a corresponding increase in reactor power. Secondly inserting control rod increase relative number of parasitic absorptions. This causes the loss component to be greater than neutron production ($k < 1$) and the neutron population begins to decrease. When the new target power level is approached, control is moved towards its previous position until k becomes unity. The reactor is now critical at the new steady state power level. In an operating reactor, the value of k is always very close to unity (White, 2011). As such it is always very convenient to quantify the amount of deviation from criticality instead of the value of k directly. To do this we define a new term called reactivity (ρ) as a measure of the deviation from critical.

$$\rho = \frac{k-1}{k} \qquad 3$$

We often talked about the insertion of positive or negative reactivity when the control rods are moved within the system. If the rods are inserted, this adds more absorption, k becomes less than unity and we say the negative reactivity has been added to the system. If the control rods are moved outward a little, then positive reactivity has been added, the absorption term decreases and k becomes slightly greater than unity.

CONCLUSION

All nuclear reactor systems are usually constructed and tested on paper before the actual manufacture and the real system are expected to behave as predicted by the reactor physics computer calculations. A number of reactor physics computer codes have already been used here in Nigeria to perform a repeat design calculation for the present Nigeria Research Reactor-1 (NIRR-1). The results obtained from various reactor physics calculations performed for this reactor system were in good agreement with experimental results as well as the results from a similar calculation performed by China Institute of Atomic Energy (CIAE), the designer/manufacturer of NIRR-1. Nigeria has the potential of engaging the services of the country’s nuclear scientist to design a nuclear power reactor for the development of the country's nuclear power program. Today, the majority of facilities used to generate electricity in Nigeria were imported finished products from sister countries. Therefore, it is extremely important we begin to introduce the practice of self-help in our search for lasting solution to some of our national problems. The country's over-dependence on the imported finished products has (directly or indirectly) retarded the growth of science and technology in Nigeria. The recent proposal to obtained four nuclear power plants (from Russia) for electrical production in Nigeria without any proposal for our nuclear scientist to learn how to design and develop such facility here in Nigeria might not speedup the growth of the NIGERIA nuclear power program. Currently, Nigeria has no experience to develop and operate a nuclear power plant for electrical production. But it has the potential of studying the success records of nuclear power program from sister countries to develop its own experience on the use of nuclear energy for electricity production. This will have a more positive impact on the growth of Nigeria's Nuclear Power Program as compared to engaging the services of a foreign firm to design, construct, operate and decommission a nuclear power plant for electricity production in Nigeria.

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