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Sodium fast reactors as potential nuclear power plants in Nigeria's quest for nuclear electricity

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Abstract

The sodium fast reactor (SFR) was x-rayed in this work as a possible candidate for the Nigeria nuclear programme. In particular, the fuel economy and effects of reactivity were analyzed using the BN 600 as a prototype nuclear power plant (NPP). In a regime of closed fuel cycle, fast reactors are reputed for utilizing a large variety of fuels in sharp contrast to conventional reactors. Reaction rates and isotopic compositions of fuel elements were computed using the software "TIME 26". The radial heat profile in the reactor core (RC) was aligned. Alignment was carried out by fuel enrichment in the peripheral part of the Active Zone (AZ), that is, Zone of Big Enrichment (ZBE). The corresponding fuel enrichment in the Zone of Small Enrichment (ZSE) was equally determined via a prompt enrichment factor (α) that ranges from 1.2 to 1.3. Parameters such as fuel campaign time and time interval between refueling were also determined. These parameters were limited to the maximum allowable burn-up value of the fuel which was set at 10%. With a Breeding Ratio (BR) of 1.2865, it is shown in this work that SFRs are able to reproduce their own fuel in contrast to thermal reactors. Further, the computed reactivity margin of 0.01283 is a key requirement for the plant internal safety. The implication for the Nigeria nuclear energy programme is discussed.

Keywords: Nuclear energy, Sodium Fast Reactor, BN 600, Nuclear fuel, Reactivity Effects

1. Introduction

The recent partnership agreement signed by Nigeria and Russia to kickstart the Nigeria nuclear programme with a Nuclear Power Plant (NPP) that will become operational in 2025 (WNN, 2017) is a welcome development in the country's quest to solve its persistent energy crises (Etukudor et. al., 2015). The agreement was a furtherance of a memorandum of understanding signed between the Nigeria Atomic Energy Commission (NAEC) and the Russian State Atomic Energy Corporation known as ROSATOM to build and operate a NPP as well as a research centre that would house a nuclear research centre which will include a multi-purpose research reactor. This is expected to be followed with additional three NPPs that will increase the total nuclear power generation capacity to 4800 MWe by 2035. Now there are quite a number of factors including both general and country specific ones which determine the choice of NPP technology to be adopted in a new nuclear power programme (Gueorguiev and Mahadeva Rao, 2005; Goldberg and Rosner, 2011; Locatelli and Mancini, 2012). Apart from the site location (Alonso, 2012; Fairley, 2017), some of the keys factors include a commensurate construction and maintenance cost, safety design, fuel economy, security, non-proliferation and waste management issues. Though the Russian nuclear programme has been involved in the research and development of all generations of nuclear reactors (Pomper, 2009), it has focussed and collaborated with other global giants on nuclear technology on the generation IV nuclear reactors which are nuclear fast reactors (FR) (Waltar and Reynolds, 1986; Waltar et. al., 2012; Aoto et. al., 2014; Ohshima and Kubo, 2016; GIF, 2017). The reason among other merits, is that the FR has been identified as a reliable means of ensuring fuel conservation with two unique characteristics: (1) the ability to breed fuel, allowing nuclear fission reactors to provide a very long-term energy supply without polluting our atmosphere (2) the ability to fission or transmute objectionable constituents of "high level waste" into elements with much shorter half-lives, thereby reducing the nuclear waste storage process from potentially thousands of years down to considerably less than a thousand year and (3) over 400 reactor-years experience has been gained in operating them. Thus the FRs are believed to be a technological step beyond conventional power reactors and are poised to become mainstream nuclear power source (WNA, 2018). This is why the IAEA's INPRO program involving 22 countries under the aegis of Generation-IV International Forum (GIF) adopted the FRs as a major emphasis. Its hi-tech technology, however, requires a lot of experience and therefore only few countries which include Russia, USA, France and Japan have developed their own FR design. In general, the

FRs are high temperature reactors fuelled by a plutonium/uranium blend and cooled using an inert gas or liquid metal to avoid any neutron moderation and provide a very efficient heat transfer medium. Now there are four general types of FRs: sodium-cooled, lead-cooled, gas-cooled and molten salt. However, only the sodium fast reactors (SFRs) have been built on large scales and there have been continuous GIF collaborative framework where various R&D activities are progressing on design of system and component, safety and operation, advanced fuel, and actinide cycle for the SFR development (Kelly, 2014). Thus the framework has continue to promote collaboration by sharing the past experience and the latest data of design and R&D among countries developing SFR (Aoto et. al., 2014; Ohshima and Kubo, 2016). However, more than any other country, Russia has continued to advance its SFR development program with more focus on their BN reactors (Buksha et. al., 1997; Kuzmin et. al., 2015). The current largest SFR in operation is the BN-800 that has a generating capacity of 800 MWe built at the Beloyarsk Nuclear Power Station (BNPS), in Zarechny, Sverdlovsk Oblast, Russia while the world's second most powerful SFR in operation is the BN-600 that has a generating capacity of 600 MWe that was earlier built at the BNPS. Though there is ongoing design and construction of the BN-1200 at the same BNPS that has a generating capacity of 1200 MWe, the focus of this current study is on the neutron-physical characteristics of the BN-600 as a starting NPP in Nigeria. The reason is that it uses mixed uranium-plutonium oxide (UO2-PuO2) fuel so that part of the nuclear waste can be recycled thereby reducing the burden of nuclear waste management which has been a serious challenge to the Nigeria nuclear programme (Chad-Umoren1 and Ebiwonjumi, 2013; Oludare et. al., 2014). Further, the BN-600 does not require a moderator which is an additional cost in NPP construction (Matveev and Homiakov, 2012; Enivwere et.al., 2017).

2. Methodology

As stated above, a FR most often uses plutonium as its basic fuel, since it fissions sufficiently with fast neutrons to keep the chain reaction going. At the same time the number of neutrons produced per plutonium-239 fission is 25% more than from uranium: this means that there are enough neutrons (after losses) not only to maintain the chain reaction but also to continually convert U-238 into more Pu-239. Therefore, fuel candidates for SFR consist of arrays of isotopes of uranium and plutonium. They include:

a) Natural uranium (0.7% ^{235}U and 99.3% ^{238}U)

b) Depleted uranium (0.2% ^{235}U and 99.8% ^{238}U)

c) Weapon grade plutonium (93% ^{239}Pu and 7% ^{240}Pu)

d) Plutonium from conventional NPPs (60% ^{239}Pu, 25% ^{240}Pu, 11% ^{241}Pu and 4% ^{242}Pu)

SFR uses a combination of oxides of ac, ad, bc or bd. The fuel used for this study is a mixture of natural UO_2 (^{235}U - 0.7% and ^{238}U - 99.3%) and weapon grade PuO_2 (^{239}Pu - 93% and ^{240}Pu - 7%) in the respective ratio of 0.85 to 0.15. The initial isotopic composition of every fuel component and that of the coolant was computed using the common relation

$$\rho_{fi} = \frac{\gamma}{M} \times 0.6 \times 10^{24} \times \varepsilon_f \, (nuclei/cm^3) = \frac{\gamma}{M} \times 0.6 \times \varepsilon_f \, (nuclei/Barn.cm) \qquad (1)$$

where ρ_{fi} is the initial isotopic concentration of fuel component i, γ is the density of fuel, M is the atomic mass of fuel and ε_f is the fractional volume of fuel in elementary cell.

Using the code "TIME 26" co-designed by one of us (A.V.A) (Apse and Shmelev, 2008), the physical and neutronic parameters were computed in a one-dimensional cylindrical model reactor with fast neutrons in a 26-group diffusion approximation. Starting with the initial isotopic composition given by Eq.(1), this code accounts for change in isotopic composition of fuel as time evolves in the reactor (Kuzmin et. al., 2015).

2.1. Enrichment of plutonium fraction of fuel

The reactor core (RC) is divided into two parts with a height of 120 cm each. The first part is the active zone (AZ) whose radius is 107.4 cm and a blanket surrounding the active zone whose thickness is 40 cm. AZ was further sub-divided into two zones: Zone of Small Enrichment (ZSE) and Zone of Big Enrichment (ZBE). The share of plutonium fraction x(PuO_2) in mixture with uranium fraction UO_2 at which effective coefficient of multiplication of neutrons (K_{eff}) equals unity was computed as follows:

$$\text{x}(PuO_2) \text{ in mixture with } UO_2 = \frac{\rho(Pu)}{\rho_f} = \frac{1.1806 \times 10^{-2}}{1.1934 \times 10^{-2}} = 9.89\% \, . \qquad (2)$$

Unaligned heat energy field in the core has adverse effect in reactor operation. In order to align the radial field of heat energy released, the share of plutonium fraction in fuel of ZSE was taken as 9.89%. Furthermore, to evaluate the share of PuO_2 in fuel of ZBE, a prompt enrichment factor (α) that ranges from 1.2-1.3 was introduced. By definition, α is the ratio of PuO_2 in ZBE to PuO_2 in ZSE. The value of α was evaluated as 1.3 yielding enrichment in ZBE as:

$$x(PuO_2)_{ZBE} = \alpha\ (9.89\%) = 12.86\%. \quad (3)$$

The normalized heat energy distribution in the reactor core after alignment is shown in Figure. 1 with radial component (r) on the horizontal axis and heat energy Q on the vertical axis. Observe that the heat energy released aligned with maximum heat energies in both ZSE and ZBE are very close (i.e. $Q_{max}(ZSE) \approx Q_{max}(ZBE)$).

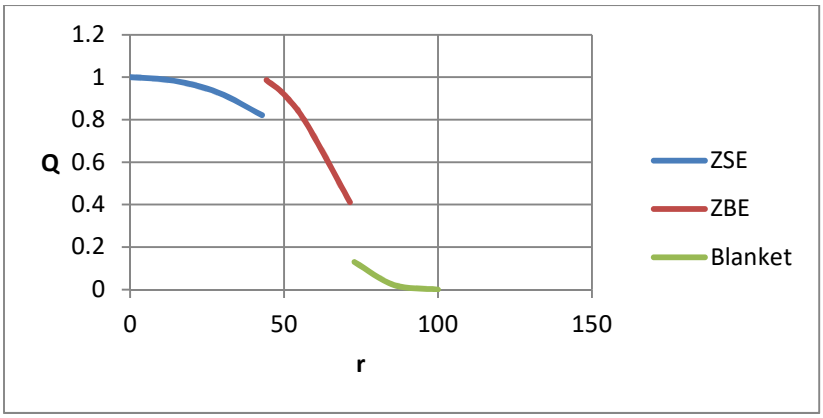

Figure. 1: Normalized radial heat energy distribution of reactor core after alignment

2.2. Breeding ratio (BR) of the reactor

Every reactor is characterized by a conversion ratio (CR) defined by:

$$CR = \frac{FP}{FD} = \frac{RR_c^{FP}(r,t)}{RR_a^{FD}(r,t)} \quad (4)$$

where FP is the fissile material produced, FD is the fissile material destroyed, $RR_c^{FP}(r,t)$ and $RR_a^{FD}(r,t)$ are the reaction rates of capture and absorption respectively. If CR < 1, such reactor (thermal) is called a converter while if CR > 1, the reactor is called a breeder. In the later case, the CR is called a breeding ratio (BR) defined as:

$$BR = \frac{Rate\ of\ production\ \ of\ secondary\ fuel\ (239_{Pu}, 241_{Pu})}{Rate\ of\ consumption\ of\ \ primary\ \ fuel\ (239_{Pu}, 241_{Pu}\ \ 241_{Pu})}. \quad (5)$$

For ZSE, BR is evaluated as

$$BR_{ZSE} = \frac{A_1}{B_1}. \quad (6)$$

where $A_1 = N_c(^{238}U)_{ZSE} + N_c(^{240}Pu)_{ZSE}$; $B_1 = N_{cf}(^{235}U)_{ZSE} + N_{cf}(^{239}Pu)_{ZSE} + N_{cf}(^{241}Pu)_{ZSE}$,

with N_c being the rate of capture and N_{cf} the rate of absorption (capture plus fission).

The BR in ZBE is evaluated as:

$$BR_{ZSE} = \frac{A_2}{B_2}. \quad (7)$$

where $A_2 = N_c(^{238}U)_{ZBE} + N_c(^{240}Pu)_{ZBE}$; $B_2 = N_{cf}(^{235}U)_{ZBE} + N_{cf}(^{239}Pu)_{ZBE} + N_{cf}(^{241}Pu)_{ZBE}$.

Breeding ratio in the active zone ($BR_{a.3}$) was then evaluated as:

$$BR_{Active} = \frac{A_1 + A_2}{B_1 + B_2} = 1.0439. \quad (8)$$

Similarly, BR in the blanket is expressed as:

$$BR_{Blanket} = \frac{N_c(238_U)_{Blanket}}{B_1 + B_2} = 0.2216. \quad (9)$$

Finally, the Breeding ratio of the entire reactor ($BR_{Reactor}$) is given as:

$$BR_{Reactor} = BR_{Active} + BR_{Blanket} = 1.0649 + 0.2216 = 1.2865 \quad (10)$$

2.3. Determination of Operation Period of Reactor in-between Refuelling, Campaign Period of Fuel and Changes in Reactivity Margin

Reactivity (ρ) is defined in terms of effective neutron multiplication factor (K_{eff}) as follows:

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \quad (11)$$

For values of $K_{eff} < 1$, $K_{eff} = 1$ and $K_{eff} > 1$, the fission reaction is said to be sub-critical, critical, super-critical respectively. In the course of operation of the reactor, processes such as burning of fissile isotopes, accumulations of secondary fuel and fission products (especially Xenon) can lead to positive and negative reactivity. These competing processes can cause a transition of the reactor to a subcritical state (Waltar and Reynolds, 1986). In order to restore reactivity margin, there is need to shutdown the reactor and carry out refueling. The maximum allowable fuel burn-up before refueling was chosen as 10%.

The period of campaign of fuel (time of accumulation of sufficient quantity of fission products) in every zone of the core was calculated using the relation:

$$T_i(days) = \frac{P_{frg,i} \times P_{f,i} \times V_i}{0.0027 W_i K_z} \quad (12)$$

where $P_{frg,i}$ is the rate of accumulation of fission fragments in *i* zone, $P_{f,i}$ is concentration of fuel in *i* zone, V_i is the volume of *i* zone, W_i is thermal power of *i* zone and K_z is axial coefficient of non-uniformity of thermal field. Taking into account Eqs.(11) and (12), the period of campaign of fuel for duo zones ZSE and ZBE were calculated as 2.2 years and 2.5 years respectively.

Refueling was carried out at intervals of 110 days (Figure. 2) and the corresponding maximum K_{eff} was calculated as 1.01283.

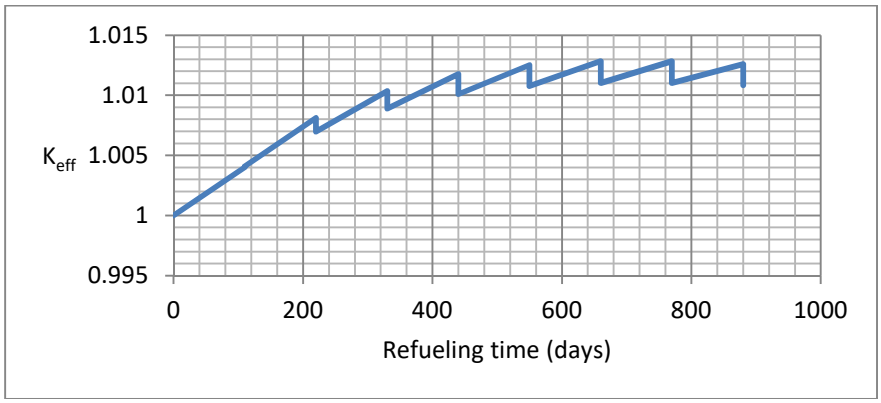

Figure.2: Dependence of K_{eff} on time of operation of reactor during refueling

2.4. Control rods and effects of reactivity in the reactor

The active zone of BN-600 consists of 4 groups of control assemblies namely:

1. Control Rods or Regulatory Assembly (RA) – neutron absorbers (B_4C) used for regulating power level by introducing small positive or negative reactivity change. Natural boron consists of 20% ^{10}B and 80% ^{11}B, but ^{10}B possesses significantly bigger capability to absorb neutrons. It is recommended that the maximum positive reactivity ΔK(RA) should not be more than the effective fraction of delayed neutrons (β_{eff}); i.e $\Delta K(RA) \leq \beta_{eff}$. β_{eff} was calculated as 0.00361.
2. Emergency Protection Assembly (EPA) – the total negative reactivity introduced by this assembly is 0.035.
3. Assembly for compensation of temperature effect of reactivity (ACT) is the total reactivity introduced by this assembly is 0.015 (Kuzmin et. al., 2015).
4. Assembly for the compensation of reactivity margin (ACRM) – this was calculated not to be less than 0.01283 for the considered fuel.

ZSE was subdivided into a system of concentric layers, thickness of which corresponds to the quantity of fuel assemblies and their dimensions. Since the reactivity effect introduced by a control rod is proportional to the K_{eff} derivative of the concentration of the ^{10}B isotope, it becomes possible to determine the reactivity effect introduced by one control rod when placed in an arbitrary layer (Matveev and Homiakov, 2012). This was computed using the relation:

$$\Delta K_{RA,i} = \Delta K(centre)\frac{dk_{eff}}{d\rho(10_B)_{RA,i}} \quad (13)$$

where $$\frac{dk_{eff}}{d\rho(10_B)_{RA,i}} = \frac{1}{N_i}\left(\frac{dk_{eff}}{d\rho(10_B)_i}\right) \quad (14)$$

is sensitivity of K_{eff} to change in concentration of ^{10}B in a control rod placed in the layer *i*; $N_i = 6(i-1)$ is the quantity of fuel assembly in layer *i*. Using the above relation, the effect of reactivity introduced by one control rod placed in an arbitrary layer was calculated.

3. Presentation and Discussion of Results

From the changing isotopic composition of fuel, the code "TIME 26" was able to estimate the coefficient of non-uniformity of the thermal field as 1.2174. This value is within the acceptable range of 1.2 - 1.4 compared to the theoretical value of 2.317 which is often rejected for practical uses (Apse and Shmelev, 2008). Furthermore, the calculated fuel fractions of PuO_2 in ZSE and ZBE are 9.89% and 12.86% respectively and this implies we do not need high quantity of weapon grade plutonium to operate the NPP. Breeding ratios in the active zone and the entire reactor were calculated as 1.0649 and 1.2865 respectively. In analyzing reactivity effects, the weight of one control rod at the center of active zone (ΔK at center) was computed as 0.00517. This maximum reactivity effect of the reactor indicates that effective reactor control is a function of the position of control mechanisms in the active zone. For using fuel with high thermal conductivity and providing good thermal contact between fuel and cladding by filling fuel, that is, cladding gap with sodium make it possible to minimize temperature and power reactivity effects. Therefore reactivity margin required for compensation of these effects should be small to avoid not only reactivity accidents caused by prompt neutrons but also fuel and fuel element cladding steel melting in the sodium cooled reactors. The reactivity margin in burning of fuel (ΔK) we obtained here is 0.01283 which is quite small and significantly lower than in the other types of reactor units (Matveev et. al., 2015).

4 Conclusion

The results of this study showed that the fuel fractions of PuO_2 in ZSE and ZBE are 9.89% and 12.86% respectively. This confers an advantage of low quantity requirement of weapon grade plutonium on the choice of fuel in our prototype SFR. Therefore the production and management of weapon grade plutonium is not required in the Nigeria nuclear programme. This obviously curb any threat of adding Nigeria even in the future to the ongoing multinational demilitarization of stockpiled nuclear weapons to reduce potential proliferation risk and management (DeVolpi, 2015). Another merit of SFR is its flexibility in using various fuel combinations. Further, a good proportion of fuel which is hitherto considered waste could be recycled in a regime of closed nuclear fuel cycle. This makes the SFR an attractive energy source for nations like Nigeria that desire to make the best use of limited nuclear fuel resources and manage nuclear waste by closing the fuel cycle (GIF, 2017). Most paramount in this research is the proven ability of an SFR to breed fuel. With a breeding ratio of 1.2865, this reactor is capable of producing 28% of its fuel at the end of a fuel campaign. This is a huge economic benefit credited only to fast breeder reactors. In her quest for nuclear electricity generation, Nigeria could take advantage of this fuel subsidy provided by SFR. Further, the safety management of the BN 600 has continued to be improved upon since it began operation in 1980 (Sofu, 2015: □ochkarev et. al., 2016; Enivweru et. al., 2017). For example, one key requirement for internal safety is to keep the maximum reactivity margin below the delayed-neutron fraction and the exclusion of the possibility of increasing power on prompt neutrons. The small reactivity margin of 0.01283 obtained here can still be reduced as the SFR technology is advanced (Matveev et. al., 2015). Ipso facto, the SFR technology is now a well understood technology and therefore, there is no need to invent anything new both in the breeding capacity and safety management if it is to be adopted in Nigeria. Thus we are led to conclude here that Nigeria can urgently take the correct steps towards the deployment of nuclear energy to solve its persistent energy problem.

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