4. AN ANALYSIS OF SAFETY MEASURES INHERENT IN FAST REACTORS MAKING THEM SITUABLE FOR NIGERIA NUCLEAR PROGRAMME †

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Abstract

There have been three major nuclear accidents in Nuclear power plants (NPPs) in the world. They include the Three Mile Island accident in 1979 (level 5), the Chernobyl accident in 1986 (level 7), and the Fukushima Daiichi accident in 2011 (level 7). In this paper, we have analyzed the causes of these three major acceidents and how the lesson learnt from them can benefits the safety precautionary measures needed in Nigerian choice of NPPs. All three severe accidents had their root causes in system deficiencies indicative of poor safety management and poor safety culture in both the nuclear industry and government authorities. We then analyzed the design of four emergency situations in the fast reactors (FRs) which emanated from the past accidents using the Fast Reactor Inherent Safety Studies (FRISS) software. We observed from the the results that the FR is able to attain stability after perturbation without recourse to special protection. The implication is that the FR is sufficiently safe against potential heavy accidents. We therefore suggest the sodium fast reactors which have built on large scales and have been in operations for years as potential NPPs for the Nigeria nuclear programme.

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1. Introduction

Nigeria has a population of 182 million with a growth rate of 3.5% (Bello. 2016). Therefore taking into account the rule of thumb for any developing industrial nation that a miimium of one gigawatt of electricity (1000 MWe) generation and consumption is required for every one million population, then the energy demand in the country stands at 182,000 MWe. Traditional electricity sources such as hydro, oil and gas currently provide an installed capacity of 14,000 MWe with availability which is fluatuating frequently less than 6,700 MWe. To salvage this energy crisis which is a long lingering problem (Etukudor et.al., 2015), the Government of Nigeria had made an informed decision in 2006 to diversify the energy portfolio to include Nuclear Power Plants (NPPs) as a long term solution. It was projected by the then Director of the Energy Commission to provide a future installed electricity generation capacity of 9.4% of the electricity demand of the country by 2015 (Sambo, 2008). However, more than a decade now, the Nigeria nuclear programme is still in limbo. One of the challenges responsible for the delay in the Nigeria nuclear electricity programme is the safety aspect of the technology. This fear emanates from the very disastrous nature of previous nuclear accidents in some of the major players in the nuclear technology (Brumfiel, 2013).

The purpose of this current paper is to analyze the inherent safety measures of the fast reactors (FRs) in order to suggest them as the possible choice of NPPs for the Nigeria nuclear programme. The motivation for this study is the recent partnership aggrement signed by Nigeria and Russia to kickstart the Nigeria nuclear programme with a target of 4000 MWe by 2025 (WNN, 2017). We point out that though Nigerians are eager to increase the country electricity generation capacity, the past disastrous nuclear accidents still scare many and this is not unrelated to poor public knowledge of the constantly advancing nuclear technology and how these accidents have positively influenced this advancement. It is our hope that this gap of pedagogical information will be remedied in this paper and is therefore planned as follows. In the Section 2, there will be basic analysis of the causes of the major global nuclear accidents with the intention to explain or point out the human and environmental factor or any other factor (be it regulatory or design) that caused the accident and then quickly explain why the causes are not tenable in our suggested NPPs for Nigeria. In Section 3, we will analyse how the lessons learnt from those accidents have help in the design of four emergency situations in the FRs. Also in this section, the Fast Reactor Inherent Safety Studies (FRISS) software will be used to analyze these four emergency situations. The results will be presented and discussed in Section 4 and this will be followed by a conclusion.

2. Analysis of the Major Nuclear Accidents

Nuclear accidents are ranked based on severity using a logarithmic scale called the International Nuclear and Radiological Event Scale (INES) developed by the International Atomic Agency in 1990. The scale ranges from 1 to 7, where Levels 4–7 are termed "accidents" and Levels 1–3 "incidents" (IAEA, 2009). Events without safety significance are classified as "Below Scale/Level 0". Events are considered in terms of their impact on three different areas: impact on people and the environment; impact on radiological barriers and controls at facilities; and impact on defense-in-depth (Högberg. 2013). There have been three major nuclear accidents that shocked the world. They include the Three Mile Island accident in 1979, the Chernobyl accident in 1986, and the Fukushima Daiichi accident in 2011.

The Three Mile Island NPP is a Pressurised Water Reactor (PWR). An operational disturbance at the plant created a slight pressure increase in the reactor system. As a result a relief valve on top of the so-called pressurizer opened and stuck in the open position, causing continuous loss of steam and hence water from the reactor primary system. As a consequence, the core boiled dry and overheated resulting in a partial core melt. This accident which was ranked Level 5 as it didn't record any onsite death, became a catalyst for major efforts by the nuclear utilities and their regulators to improve nuclear plant safety (David et. al., 1996).

The Chernobyl NPP is a graphite-moderated channel-type boiling water reactor (BWR) of a standard Soviet design known as RBMK. The accident in this NPP which occurred on April 25–26, 1986, resulted from a series of design weaknesses in the reactor that turned into a deadly disaster due to a series of operator errors and safety violations during a botched experiment. The reactor was completely destroyed and evaporated contamination of fuel and fuel fragments (fission products) were spewed high up in the air. A fire started in the remaining graphite that burned for some 10 days. This nuclear accident is ranked Level 7 and is believed to be the worst in history since 1952 as it not only killed the onsite personnel but also the contamination traveled far and wide to affect the surrounding environment and caused immense health impacts for the people living in the region. However, a lot of lessons were learnt fom this accident which have been very useful in design and operational future safety of NPPs (Clarke, 2011; Beresforda et.a.., 2016).

The Fukushima Daiichi NPP comprised of six boiling water reactors (BWRs). The immediate cause of this accident was the Great East Japan Earthquake (magnitude 9.0 on the Richter Scale), which occurred off the Sanriku coast of Japan on March 11, 2011 (Yoshizawa et. al., 2016). This earthquake sparked a tsunami whose wave was 13 m (43 ft) high, overwhelming the plant's seawall, which was 10 m (33 ft) high. Before the earthquake, , Reactors 4, 5, and 6 were shut down in preparation for re-fueling. However, their spent fuel pools still required cooling. Immediately after the earthquake, the electricity-producing Reactors 1, 2, and 3 automatically shut down their sustained fission reactions by inserting control rods in a legally-mandated safety procedure referred to as SCRAM, which ceases the reactors' normal running conditions. As designed, since the reactors were unable to generate power to run their own coolant pumps, emergency diesel generators turned on autmaically to power electronics and coolant systems until the flood destroyed the generators for Reactors 1–5. This resulted in a loss of power to the critical coolant water pumps. However, also as designed, the secondary emergency pumps powered by electrical batteries came into operation until the batteries ran out a day after the tsunami, resulting final stoppage of the water pumps and consequently the overheating and then meltdown of the reactors. This nuclear accident is ranked Level 7 and considered the worst disaster after Chernobyl in the history of NPPs since 1952.

It is pertinent to point out here that the lessons learnt from these accidents have helped in advancing the safety aspects of modern working reactors technologies beyond the accidents' causes (Nature, 2006; Geist, 2014; Yoshizawa et. al., 2016). For example, the FRs which we will analyzed their safety technology in the next section and later suggest for theNigeria nuclear programme, are not susceptible to Chernobyl-style accident. On the environmental impact, it is worthy to note that the probability of the Fukushima accident happening in Nigeria is close to zero. This is because, unlike Japan, Nigeria is not located on tectonic plates that are prone to frequent disastrous earthquakes.

3. Analysis of the Four Emergency Situations in Fast Reactors

Now the causes of the three major nuclear accidents analyzed in the preceding section and the lessons learnt from them have engendered safety as a major component of NPP design and operation. Particular attention is paid to providing protection against accidents due to the use of intrinsic properties of structures and protection systems, which are based on passive principles of operation. Four emergency situations peculiar only to Fast Breeders and their various combinations analyzed in this paper are associated with a violation of operating modes and simultaneous failure of emergency protection. These violations include:

1. Violation of forced coolant circulation in the primary circuit of the reactor or Loss-of-Flow Without Scram (LOF WS). This situation can occur as a result of failure or de-energization of the main circulation pump of the primary circuit, which ultimately leads to a reduction in the coolant flow rate.
2. Unauthorized input of limited positive reactivity rate exceeding $+0.07\beta/s$ or Transient Overpower Without Scram (TOP WS). This event can occur with erroneous movement of the protection and control systems, control rods, the drop

of "fresh" fuel assembly into the active zone, which leads to slow perturbations in reactivity.

3. Violation of heat removal from the primary circuit to the surrounding media or Loss-of-Heat-Sink Without Scram (LOHS WS). Such an event is associated with a violation of the balance between incoming and outgoing heat. It can be caused by loss of the coolant of the second circuit or a violation of the forced circulation of the coolant in this circuit, which leads to an increase in the input temperature of the coolant.

4. Cooling of primary coolant or Overcooling Accident Without Scram (OVC WS). It is a special case of the TOP WS process and is modeled by lowering the coolant input temperature or increasing its flow rate.

The above mentioned emergency situations were investigated using the FRISS software. This program has the ability to investigate non-stationary processes in fast reactors with a liquid-metal coolant caused by external influences, leading to perturbations of reactivity, the temperature of the coolant at the entrance to the active zone, the flow of the coolant and their various combinations. It also determines the range of permissible perturbations of reactivity, inlet temperature and coolant flow rate, in which reactor safety is ensured by its inherent properties without recourse to special protective means.

It is pertinent to point out that the FRISS software though very effective but not so complex to use because the code only requires the input of the reactor parameters that are in violation of normal modes of operation. For LOF WS analysis, the pump running time was 20 seconds instead of 100 seconds or more. For TOP WS analysis, the value of introduced reactivity perturbation is +0.5β. For LOHS WS analysis, the coolant inlet temperature was increased to 800 K in 10 seconds; while for OVC WS analysis, the coolant flow rate was increased to 1.5 (relative units) within a time period of 10 seconds.

4. Presentation and Discussion of Results

Fig. 1 is the graphical presentation of the results for the time evolution of the Loss-of-Flow Without Scram (LOF WS) depicting the variation of (a) Coolant outlet temperature Tc (K) with time t(s) (b) maximum fuel temperature Tf (K) with time t(s). In Fig. 1(a), as we reduce the pump running time to 20s, coolant outlet temperature rose to 1120 K and later produced a plateau of lower stable temperatures after 70s. The same event was observed for fuel maximum temperature in Fig. 1(b).

Fig. 2 is the graphical analysis of the time evolution of the Transient Overpower Without Scram (TOP WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s). By introducing a positive reactivity of +0.5β, coolant outlet temperature increased from 785K to 808K in 10s (Fig. 2(a)). Thereafter, the rising gradient weakened giving way for a stable temperature of 817 K after 50s. The event observed in Fig. 2(b) was similar to that in Fig. 2(a). Fig. 3 is the graphical analysis of the time evolution of the Loss-of-Heat-Sink Without Scram (LOHS WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s).

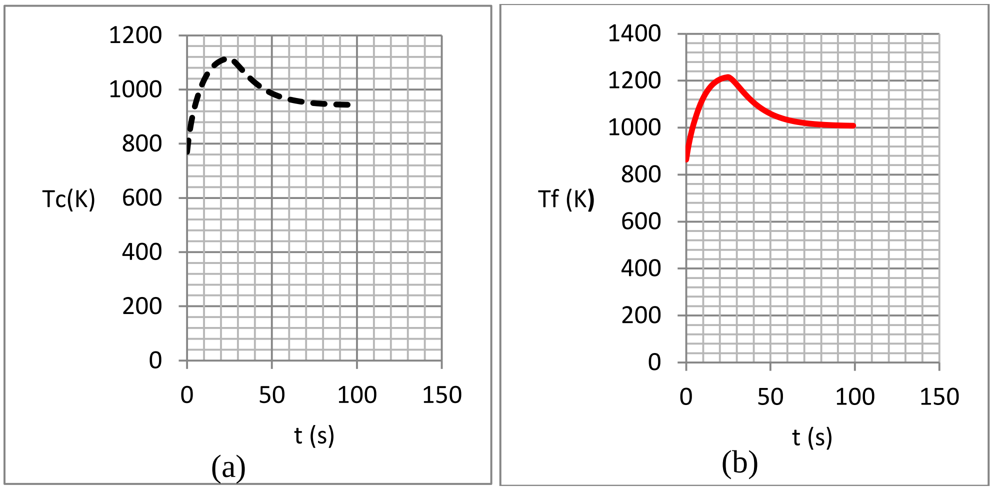

Fig. 1 The graphical analysis of the time evolution of the Loss-of-Flow Without Scram (LOF WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s)

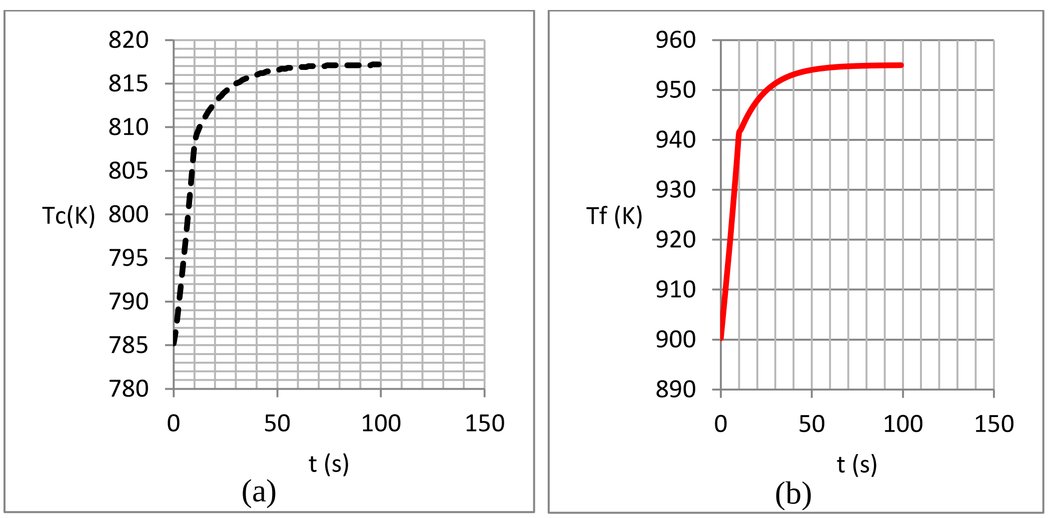

Fig. 2 The graphical analysis of the time evolution of the Transient Overpower Without Scram (TOP WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s)

In Figs. 3(a) and 3(b) coolant outlet and fuel temperatures dropped rapidly after coolant inlet temperature was increased to 800 K in 10s. Fig. 4 is the graphical analysis of the time evolution of the Overcooling Accident Without Scram (OVC WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s). As we increase the coolant flow rate from ratio 1 to 1.5, coolant spent less time in the core and as a result couldn't carry much heat energy from the core. This resulted in coolant overcooling from 770K to 730K in 10s and later stabilized at 733K after 50s (Fig. 4b). Similar scenario was replicated in fuel maximum temperature (Fig. 4b).

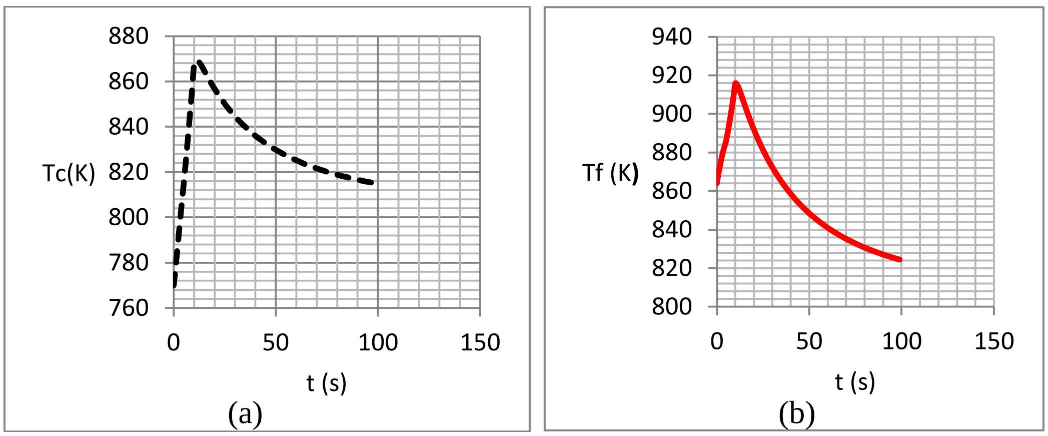

Fig.3 The graphical analysis of the time evolution of the Loss-of-Heat-Sink Without Scram (LOHS WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s)

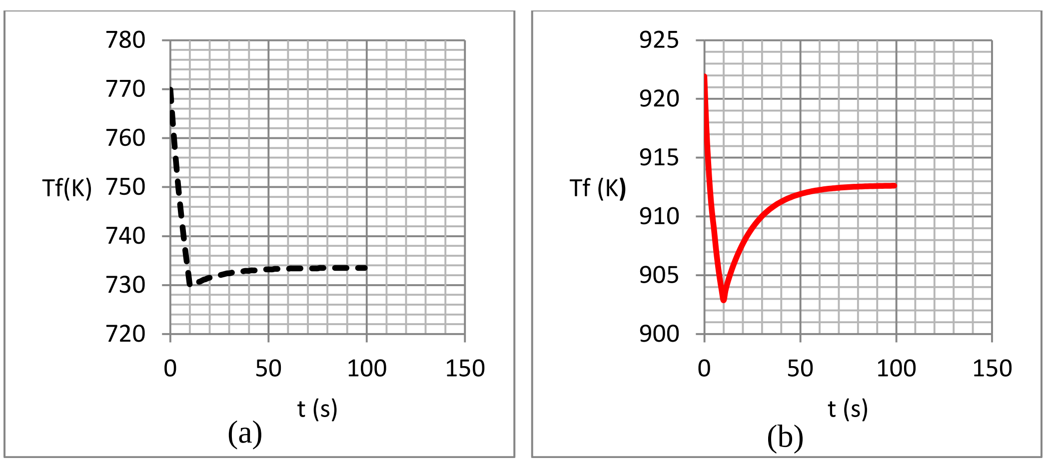

Fig. 4 The graphical analysis of the time evolution of the Overcooling Accident Without Scram (OVC WS) depicting the variation of the (a) Coolant outlet temperature Tc (K) with time t(s) (b) Maximum fuel temperature T_f (K) with time t(s)

5. Conclusion

We have demonstrated in the preceding section that from the computed results obtained in Section 3, the FR is sufficiently safe against potential heavy accidents. For in the plots of maximum fuel temperature and coolant outlet temperature versus time for various emergency processes, the plateau in the Figs 1-4 indicates that the reactor is able to attain stability after perturbation without recourse to special protection.

Now there are four general types of FRs: sodium-cooled, lead-cooled, gas-cooled and molten salt. As the names connotes, the coolants in these reactors are sodium, lead, gas and molten salt respectively and not water However, only the sodium fast reactors (SFRs) have been built on large scales (Matveev and Homiakov, 2012). The reason is that. apart from the sodium being coolant, the fuel tablet also has a little quantity of sodium in the contact layer (gap between the fuel and the steel clad). So in the event of loss of coolant after the fission process is stopped, the sodium in the contact layer is able to address the overheating challenge in the core before a special protections means is triggered.

Finally, it is pertinent to mention that the FR also has the capability to reproduce some percentage of its fuel which can be used for refueling after the first campaign period which is usually between 2 to 3 years; hence they are also known as fast breeders (FBs). This is very good for fuel economy as well as nuclear waste management. Therefore, the sodium fast reactors are potential NPP candidates for the Nigeria nuclear programme not only because of their inherent safety precautionary measures but also because of their fuel economy and waste management.

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