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Toward Transparency and Broader Safeguards Conclusion: A Closer Look at the Proposed Saudi's Civilian Nuclear Power Program

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Abstract—The higher the transparency of any civilian nuclear power program, the higher the chance of attracting and securing the long-term foreign nuclear cooperation. For newcomer states, securing nuclear cooperation is essential for successful deployment and implementation of nuclear power program. Complying with an acceptable types of safeguards commitment/protocols plays a major role in increasing transparency. The determination of transparency primarily relies on the presence of sensitive nuclear isotopes–as defined under IAEA's safeguards–with a nuclear facility. Kingdom of Saudi Arabia (KSA) is considering the deployment of civilian nuclear power program with a projected nuclear capacity ~18 gigawatt-electric (GWe) by 2032-40. The goals of this paper were the quantification of the sensitive nuclear isotopes (primarily plutonium) that will be produced within the prospective KSA nuclear facilities up to 2040 and the estimation of the uranium fuel requirements. Two scenarios were analyzed. Scenario-I: two reactors are operational started by 2022 and one reactors are added each year subsequently until the intended 11 reactors are deployed. Scenario-II is like Scenario-I, but only one reactor is added each two years subsequent to the deployment of the first 2 reactors in 2022. Simulation of EPR operation was performed from beginning of life to equilibrium cycle using Monte Carlo N-Particle (MCNP6) code. A 2-year cycle length was assumed.

The proposed KSA civilian nuclear power program would require 5766 and 4585 tonnes of cumulative uranium by 2040 for Scenario-I and Scenario-II respectively. The discharged fuel (assuming full power at 90% capacity factor) would contain 17.6 and 13 tonnes of cumulative ^{239}Pu along with 21.4 and 15.9 tonnes of cumulative total plutonium by 2040 for Scenario-I and Scenario-II respectively. A primary concern related to transparency is the ability and readiness of KSA to handle these quantities of special nuclear material under internationally acceptable safeguards protocols as the planed nuclear power program expands. It's recommended that KSA have AP in place well before 2040 to enable IAEA draw the broader safeguards conclusion which definitely will raise the confidence of the international community.

Index Terms— Additional Protocol, Broader Safeguards Conclusion, Civilian Nuclear Energy Development, MCNP Simulation, Newcomer States, Nuclear Transparency, Safeguards Commitiments.

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1 INTRODUCTION

The latest reports by the International Atomic Energy Agency (IAEA) indicate an increase in demand for nuclear power – a result of increasing electricity demand and population growth [1]. Nuclear energy is considered by many countries to be one of the safest energy sources that can produce a reasonable amount of electricity for a long period of time. Rapid population growth, increased electricity demand and limited energy resources are driving many developing states (newcomers), including the Gulf States, to consider the deployment of civilian nuclear power programs [2]. In 2010, the Kingdom of Saudi Arabia (KSA) officially announced such a deployment plan and established the King Abdullah City for Atomic and Renewable Energy (KACARE) [3]. KACARE is the KSA's representative to the IAEA. The establishment is also responsible for forming and deploying the KSA civilian nuclear power program [3].

Since the Atoms for Peace speech in 1953, many lessons have been learned in determining the essential factors for the successful deployment of civilian nuclear power programs. These factors include the ratification of the Nuclear Non-Proliferation Treaty (NPT) and the maintenance of a status of compliance with the IAEA safeguard protocols [4]. The NPT is the cornerstone of the international non-proliferation regime. It is important for newcomers to gain the confidence of the international nuclear community and attract long-term foreign nuclear cooperation. Thus, newcomer states must have an acceptable safeguard protocols in place before the deployment of their civilian nuclear power programs.

The IAEA safeguards system involves a set of obligations and commitments: 1) the Comprehensive Safeguards Agreement (CSA), 2) the Small Quantities Protocol (SQP) and 3) the Additional Protocol (AP). After the discovery of the Iraqi clandestine nuclear weapon program [5], the CSA was proven to have limitations that prevented the IAEA from performing its duties effectively and sufficiently [6]. Consequently, the AP was adopted in 1997 to equip the IAEA with the needed tools to verify, deter, and provide assurances of the absence of undeclared nuclear activities [6], [7], [8]. The AP aims to strengthen the effectiveness and improve the efficiency of the safeguards system [6], [7], [8]. Moreover, the AP enables the IAEA to draw the broader safeguards conclusion [6], thereby raising nuclear transparency at the state level.

The deployment of a civilian nuclear power program comes with the need for a high level of nuclear transparency. Jeemin Ha et al. (2014) defined nuclear transparency as referring to various forms of openness that enhance international

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confidence and understanding in nuclear matters regarding a country [9]. Another definition of nuclear transparency also refers to openness [10] – which plays a major role in increasing state-level nuclear transparency. Such openness requires compliance with acceptable safeguard commitments that allows the IAEA to provide assurances of the absence of undeclared nuclear activities in state.

2 SCOPE OF WORK

In this study, fuel cycle factors affecting transparency were analyzed by quantifying the sensitive nuclear isotopes – as defined under the IAEA's safeguards – that will be produced within the prospective KSA nuclear facilities. Simulations assuming the deployment of light-water reactors were performed using Monte Carlo N-Particle (MCNP6) code. The goal of the simulations was to estimate the uranium fuel requirements and more importantly the amounts of sensitive nuclear isotopes (primarily plutonium) produced in the deployment of the planned nuclear power program up through 2040. The results will help to reconcile the KSA's current outlook toward higher nuclear transparency and the broader safeguards conclusion. Additionally, the study discussed the needed number of reactors in accordance to the KSA's energy demand. Such discussion would allow for an accurate identification of the needed number of reactors for the KSA's civilian nuclear power program.

3 DESCRIPTION OF WORK

3.1 THE KSA PROPOSED CIVILIAN NUCLEAR POWER PROGRAM

KACARE has been involved in international agreements to evaluate, roadmap, and strategize the deployment of the KSA's civilian nuclear power program [3]. Initially, KACARE has projected the deployment of 16 power reactors to provide at least 17-18 gigawatts-electric (GWe) by 2032-2040 (see Table 1) [3]. KACARE has not officially announced the deployment of a specific type of power reactor, but both of the Evolutionary Power Reactor (EPR) designed by AREVA (a French company) and the AP1000 designed by Westinghouse (a US company) has been proposed (see Table 1) [3]. Of all the reactor types that the KSA has studied, the EPR is the most likely candidate. The Westinghouse AP1000 is unlikely to be deployed in near future because KSA has not yet signed the 123 Agreement with United States of America [3]. In contrast, KSA signed a nuclear agreement with France in 2011 and an agreement with AREVA in 2015 to undertake a feasibility study for building EPR [3]. Therefore, this study will assume the deployment of EPR.

The first two power reactors are planned to begin operation by approximately 2022, followed by the subsequent addition of one or two reactors until the intended number of reactors are completed [3]. The KSA's proposed nuclear fuel cycle involves three options: 1) importing the nuclear fuel, which does not require obtaining a local fuel fabrication and enrichment plants; 2) manufacturing nuclear fuel, which does require building local fuel fabrication and enrichment plants; or 3) a combination of the two options (see Table 1). The KSA currently has no nuclear fuel cycle capabilities [3]. If the plans of KACARE are followed precisely, the initial nuclear fuel will have to be imported when the first two power reactors come online in 2022. For nuclear non-proliferation activities, KSA were committed to NPT in 1988, SQP in 2005, CSA in 2009, and no AP has been concluded yet (see Table 1).

TABLE 1

SPECIFICATIONS OF THE PROPOSED KSA CIVILAIN NUCLEAR POWER PROGRAM

KSA	Parameter Specifications	
Nuclear Capacity	Electricity Production (GWe	Number of Nuclear Power Reactors
	17-18	16[a]
Types of Power Reactors	Name	Electricity Production (GWe)
	EPR	1600
	AP100	~1000
Nuclear Fuel Cycle	Options or Scenarios	
	1-Importation of the fuel 2-Manufacturing the fuel 3-A combination of both	
Nuclear NonProliferation Activities[b]	Agreement Name	Signature or Ratification Date
	NPT	1988
	SQP	2005
	CSA	2009
	AP[c]	-

Source: World Nuclear Association. 2016. Nuclear Power in Saudi Arabia [3].
a, The KSA's number of reactors will be further discussed in section 4.1.
b, Non-Proliferation activities are limited, list does not include all conventions.
c, KSA has not yet signed the AP.

3.2 THE MAIN SPECIFICATION FOR EPR REACTOR

The EPR is a 3rd-generation pressurized water reactor designed by AREVA. Since 2003, EPRs have been considered by China, Finland, and France for the production of electricity [11]. The EPR offers ~1600 megawatts-electric (MWe) as electrical power, ~ 36% efficiency, and a 60-year plant lifetime [11]. The main characteristics of the EPR core are described in Table 2 [11], [12]. The EPR is designed to support advanced fuel management [11], [12]. The AREVA fuel strategy covers cycle lengths of 12, 18, and 24 months [12]. From a power production perspective, a longer cycle means a better reactor availability factor. Consequently, the 24-month cycle length was considered in this study.

TABLE 2 THE MAIN CHARACTERISTICS OF THE EPR CORE

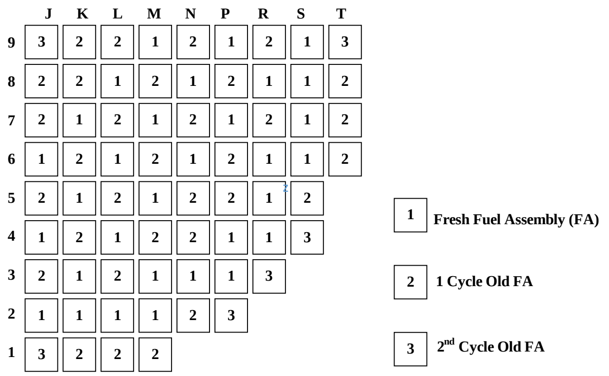
EPR Core Design	
Number of Fuel Assemblies	241
Number of Fuel Rods per Fuel Assembly	265
Fuel Assembly Array	17x17
Number of Fuel Rods	89
Number of Guide Tubes per Assembly	24
Total Fuel Height (cm)	840
Active Fuel Height (cm)	420
Fuel Assembly Pitch (cm)	21.5

Fuel Rod Pitch (cm)	1.26
Fuel Pin Diameter (cm)	0.95
Enrichment (%)	Up ro 5%-^{235}U
Batch Discharge Burnup (MWD/Kg)	55 to 65

3.3 SPECIFICATION OF THE MCNP SIMULATION MODEL

3.3.1 FUEL BURNUP

The 24-month cycle length (~720 days) was the adopted refueling scheme to allow for longer reactor availability. Therefore, The EPR loading pattern of the 24-month equilibrium cycle is presented in Fig. 1. The equilibrium fuel cycle begins with the third batch refueling cycles. The first batch of the fuel cycle consisted of 241 fresh fuel assemblies at the beginning of life (BOL). In the beginning of the second cycle, 112 fuel assemblies were discharged and replaced with 112 fresh fuel assemblies. In the beginning of the third cycle (the equilibrium cycle), 112 of the remaining fuel assemblies from the BOL were discharged and replaced with 112 fresh fuel assemblies. At this point, the core consisted of 112 fresh fuel assemblies, 112 one-cycle old fuel assemblies and 17 two-cycle old fuel assemblies (see Fig. 1). After fuel discharge, the decay of ^{241}Pu was accounted for. Due to its relatively short half-life (14.4 y), changes in the ^{241}Pu content of the discharged fuel are significant over the period of interest. The half-life is also small in comparison with other significant plutonium isotopes. The considered capacity factor is 90% along with 4500 megawatts-thermal (MWt) as EPR thermal output.



	J	K	L	M	N	P	R	S	T
9	3	2	2	1	2	1	2	1	3
8	2	2	1	2	1	2	1	1	2
7	2	1	2	1	2	1	2	1	2
6	1	2	1	2	1	2	1	1	2
5	2	1	2	1	2	2	1	2	
4	1	2	1	2	2	1	1	3	
3	2	1	2	1	1	1	3		
2	1	1	1	1	2	3			
1	3	2	2	2					

1	Fresh Fuel Assembly (FA)
2	1 Cycle Old FA
3	2nd Cycle Old FA

Fig. 1. The EPR Loading Pattern with 24-Month Equilibrium Cycle.

3.3.2 THE USED MATERIALS

The used materials in the MCNP simulation model for EPR core are described in Table 3 along with their dimensions. The reactor pressure vessel material is 16MND5. The core barrel material is assumed to be 304 stainless steel (304SS), which is the standard material that have been used in pressurized water reactor (PWR) [11], [13], [14]. For cladding and guide tube, the material is M5™ which have been manufactured by AREVA [11]. The composition of M5™ is not publicly released for intellectual property reasons. According to the U.S. nuclear regulatory commission (NRC), M5™ consists of 99% zirconium and 1% niobium [15].

TABLE 3 DESCRIPTION OF THE MAIN MATERIALS OF EPR CORE

Reactor Pressure Vessel (RPV)		
Material Name	Composition (weight %)^{a}	In and Out-Diameter (cm)
16MND5	0.16% C, 0.015% Si, 1.30% Mn, 0.007% S, 0.010% P, 0.74% Ni, 0.18% Cr, 0.48% Mo, 0.06% Cu, 0.01% Co	243.5-268.5
Core Barrel		
Material Name	Composition (weight %)^{b}	In and Out-Diameter (cm)
304SS	0.05% C, 9.00% Ni, 18.00% Cr	205-210.175
Cladding and Guide Tube		
Material Name	Composition (weight %)^{c}	In and Out-Diameter (cm)
M5™	99% Zr, 1% Nb	Cladding 0.4191-0.475 Guide Tube 0.5666-0.6225

a, Source: steeldata.info. 2016. 16MND5 Steel [13].
b, Source: steeldata.info. 2016. 304 Stainless Steel [14].
c, Source: Nuclear Regulatory Commission (NRC).2011 [15].

4 DISCUSSION AND RESULTS

4.1 THE KSA'S ENERGY DEMAND VS. THE NEEDED NUMBERS OF EPR UNITS

The goal of this section is to identify the needed number of EPR reactors for KSA's civilian nuclear power program. Such identification is based on the KSA's targeted nuclear capacity which itself based on the projected growth of KSA's electricity demand. The KSA's energy demand (electricity) is currently rely on fossil fuels, specifically oil and natural gas plants [3], [16], [17]. Due to the population growth and the need for more desalination plants (desalinated water), the annual electricity demand is subjected to substantial increase [3], [16]. Many forecasts projected the annual increase in KSA's energy demand to range from 6 to 8 % [3].

As indicated by the World Nuclear Association (WNA), KSA's energy demand targeted a total of 128.5 GWe by 2032 [3]. The targeted KSA's energy demand consist of 50 GWe by solar and geothermal, 60.5 GWe by hydrocarbon (fossil), and ~18 GWe by nuclear [3]. The KACARE's website stated the same in regard of KSA's targeted nuclear capacity (17.6 GWe by 2032) [18]. In a previous work, analysis of KSA nuclear program involving 16 EPR reactors was performed [19]. This was in line with KSA project number of power reactors. However, one unit of EPR is capable of producing 1.6 GWe [11], and therefore, the needed numbers of EPR units would be eleven. The KSA's initial nuclear targeted data was 2032, however, WNA stated that it has been put pack to 2040 [3]. Therefore, this study would consider both scenarios.

4.1.1 THE ANALYZED SCENARIOS FOR OPERATIONAL EPR

In compliance to the aforementioned information in regards of the KSA's civilian power program, two scenarios were analyzed. In scenario-I, two EPR reactors would be operational by 2022 and one EPR reactor would be subsequently added each year until the 11 reactors had been deployed (see Fig. 2). In scenario-II, two EPR reactors would be operational by 2022 and one EPR reactor would be added each two years (see Fig. 2). In both scenarios, the first equilibrium cycles would be reached by 2028. With the implementation of scenario-I, the deployment of the 11 reactors would be complete in 2031 and the last deployed reactor would reach the equilibrium cycle by 2037. With the implementation of scenario-II, the deployment of the 11 reactors would be complete in 2040 and the last deployed reactor would reach its equilibrium cycle by 2046.

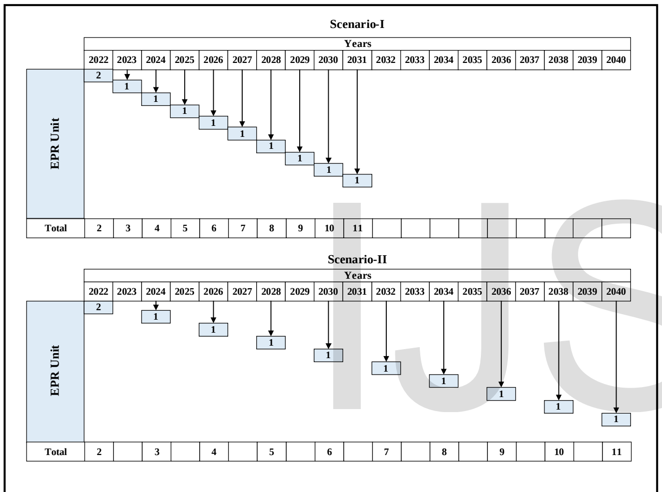
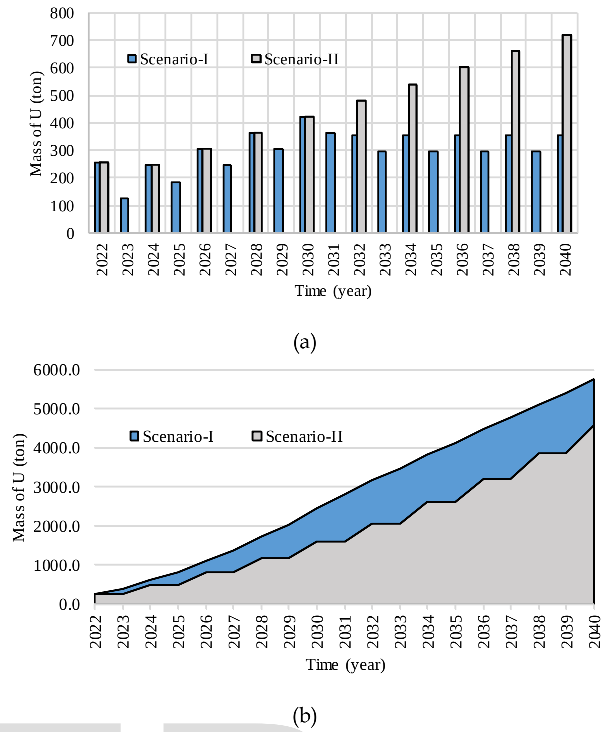


Fig. 2. The Analyzed Scenarios for 11 EPRs.

4.2 NUCLEAR FUEL REQUIREMENTS

In 2022, the KSA's civilian nuclear power program will require 254 tonnes of uranium (see Fig. 3. A) to feed the first two reactors. Under the assumption of scenario-I, a similar amount of uranium would be required each year until the completion of the 11 reactors in 2031. Scenario-I would require 236 tonnes of uranium for refueling by 2031. Once all the 11 reactors have been deployed, the annual uranium requirement will alternate between 354 tonnes and 295 tonens starting from 2032, provided the number of reactors and the refueling scheme remain the same. Scenario-I would require a total of 5766 tonnes (cumulative) of uranium by 2040 (see Fig. 3. B). Under the implementation of scenario-II, the uranium needed to fuel the reactors would peak at 717 tonnes in 2040, at which time all the 11 reactors would have been deployed (see Fig. 3. A). Scenario-II would require a total of 4585 tonnes (cumulative) of uranium by 2040 (see Fig. 3. B).



(a)

(b)

Fig. 3. Uranium Requirements; (a) annual, and (b) cumulative.

From the nuclear fuel point of view, scenario-II seems to be a better option for the KSA because of the lower rate of increase in the cumulative required uranium compared with scenario-I (see Fig. 3. B). For the first ten years (2022-32), scenario-I and II would require 3168 and 2070 tonnes (cumulative) of uranium, respectively. In scenario-I, uranium would be required each year either as fresh fuel or for refueling (see Fig. 3. A). In contrast, scenario-II would not require uranium each year (see Fig. 3. A) – the uranium requirement started at 2022 and the following year no uranium, triggering a biennial uranium resource demand. Thus, scenario-II would allow for better flexibility and lead time toward the KSA's completion of a robust strategy for safeguards and material accountability in the planned nuclear facilities. From the perspective of electricity production, scenario-I is the better option because it would provide the KSA targeted nuclear capacity (17.6 GWe by 2031). To this end, the KSA must evaluate both scenarios with respect to its nuclear fuel requirements to determine the better fit for the state.

4.3 SPENT NUCLEAR FUEL IMPACT ON SAFEGUARDS AND NONPROLIFERATION

Weapons-grade plutonium and reactor-grade plutonium are both considered potential proliferation risks [20]. By 2024, the cumulative discharged fuel (under the assumption of full power at a 90% capacity factor) would contain 894 kg of plutonium for both scenarios (see Fig. 4). An approximately similar amount would be added each year under both scenarios if the reactors were to be operated under the same conditions, including the same refueling scheme. Thus, the plutonium stock in both scenarios will continue to grow. By 2040, scenario-I would have yielded 21428 kg of plutonium, and 15986 kg would have been produced in scenario-II (see Fig. 4). There is no indication that the KSA will invest in nuclear fuel reprocessing. However, it is conceivable that the nuclear fuels may be moved. Discharged fuels require cooling in the spent fuel pools of the reactors for up to 5 years before any possible outside shipment, either for reprocessing or for transfer to a nuclear repository. Thus, the KSA must have a robust, comprehensive and complete strategy for safeguards and accountability in place well before any possible movement of discharged fuels.

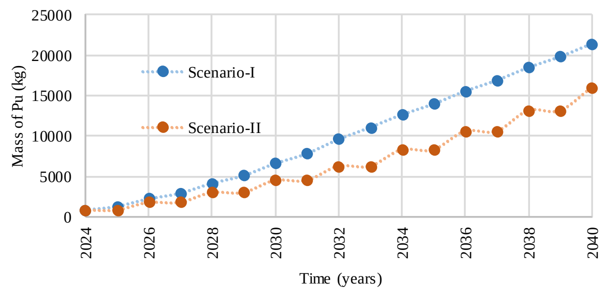
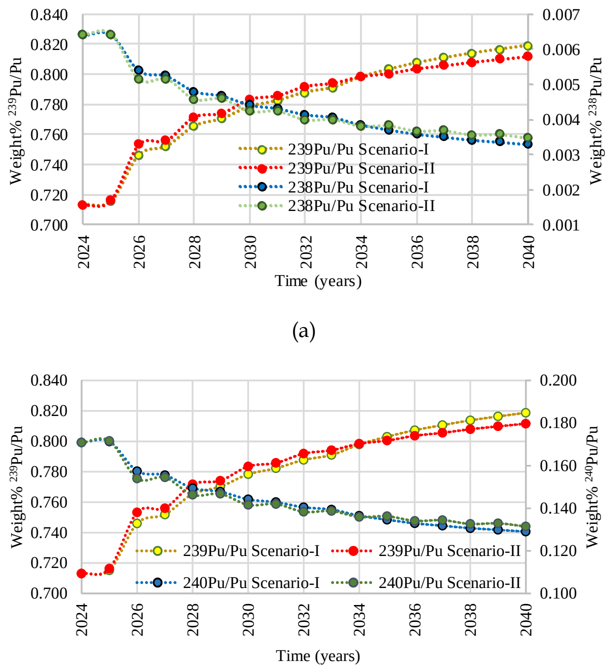


Fig. 4. Annual Plutonium Production.

Plutonium is regarded by the IAEA as a direct-use nuclear material, of which 8 kg is sufficient to produce one nuclear bomb [7]. However, ^{239}Pu is the most suitable plutonium isotope for nuclear weapons [20]. The presence of ^{238}Pu and ^{240}Pu in the plutonium vector is detrimental to the use of plutonium in nuclear weapons [20]. The weight percentages of ^{238}Pu, ^{239}Pu, and ^{240}Pu with respect to the total Pu for both scenarios are presented in Fig. 5.

The weight fraction of ^{239}Pu/Pu for both scenarios would start at 0.71% and increase over time (see Fig. 5). By 2040, 81 percent of the plutonium will be ^{239}Pu for both scenarios. By contrast, the weight fraction of ^{238}Pu/Pu for both scenarios would start at 0.0064% and decrease over time (see Fig. 5. A.). By 2040, the weight fraction of ^{238}Pu/Pu for both scenarios would have dropped to 0.0035%. The weight fraction of ^{240}Pu/Pu for both scenarios would start at 0.171% and decrease over time (see Fig. 5. B.). By 2040, the weight fraction of ^{240}Pu/Pu would have dropped to 0.129% for scenario-I and 0.131% for scenario-II.

The expected high quantities of plutonium consisting predominantly of ^{239}Pu indicate the necessity to develop a robust safeguards strategy towards; 1) high level of nuclear transparency, 2) broader safeguards conclusion. In addition, a robust safeguards strategy will allow for; 1) raising the confident of the international community, 2) attracting/securing nuclear foreign cooperation, and 3) successful deployment of civilian nuclear power program. The KSA have concluded reasonable types of safeguards commitment/protocol such as the SQP in 2005 and the CSA in 2009 [3]. However, with these types of safeguards commitment/protocol, the IAEA will not be able to conclude that there is no indication of undeclared nuclear activities in state [21]. With such types of safeguards commitment/protocol, the state's safeguards conclusion as well as the state level of nuclear transparency will be limited to the state's declarations [21].



(a)

(b)

Fig. 5. Plutonium Fractions for Both Scenarios; (a) ^{239}Pu/Pu vs. ^{238}Pu/Pu, and (b) ^{239}Pu/Pu vs. ^{240}Pu/Pu.

The IAEA's assessment to nuclear transparency in regards of safeguards and nonproliferation, includes many factors where the important one is the state compliance to the AP [10]. Therefore, in the case of KSA, further type of safeguards protocol that allow for broader access and information will be needed. Given the KSA's ambitious plan of nuclear power program and the projected quantities of direct-use materials, the KSA will need to foster its nuclear transparency. The fostering of such transparency can be achieved by agreeing to AP compliance with the IAEA, which will enable the broader safeguards conclusion and therefore raise the confident of the international community.

5 CONCLUSIONS AND RECOMMENDATION

The goals of the described work were; 1) the estimation of the required enriched uranium for fueling the proposed KSA reactors – assuming the deployment of EPR, and 2) the quantification of the amounts of sensitive nuclear isotopes, primarily plutonium, that will be stored in the proposed KSA reactors after refueling. The reactor operations were simulated using MCNP6. A two-year cycle length was assumed for the refueling strategy. For the deployment of the KSA reactors, two scenarios were analyzed. In scenario-I, two reactors would be deployed by 2022 and one reactors would be subsequently added each year until the 11 reactors had been completed. In scenario-II, two reactors would be operational by 2022 and one reactor would be added each two years towards the completion of 11 reactors.

The results indicated a total of 5766 tonnes of cumulative uranium for scenario-I by 2040 and 4585 tonnes for scenario-II. Scenario-II was suggested as a better option because of its lower uranium requirements. The result indicated a total of 21.4 tonnes of plutonium (cumulative) for scenario-I by 2040, 81% of which would be ^{239}Pu; for scenario-II, the corresponding total would be 15.9 tonnes, consisting of 81% ^{239}Pu. For both scenarios, adoption of the AP was therefore recommended as a first step in fostering transparency and enabling the IAEA to conclude the broader safeguards conclusion. This measure will raise the confidence of the international community and attract/secure foreign nuclear cooperation.

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NOMENCLATURE

IAEA	International Atomic Energy Agency
KSA	Kingdom of Saudi Arabia
KACARE	King Abdullah City for Atomic and Renewable Energ
NPT	Nuclear Non-Proliferation Treaty
CSA	Comprehensive Safeguards Agreement
SQP	Small Quantities Protocol
AP	Additional Protocol
MCNP	Monte Carlo N-Particle
GWe	Gigawatts-electric
EPR	Evolutionary Power Reactor
MWe	Megawatts-electric
MWt	Megawatts-thermal
NRC	Nuclear Regulatory Commission
WNA	World Nuclear Association
KACST	King Abdulaziz City for Science and Technology
SACM	Saudi Arabian Cultural Mission

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