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Determination of the Sensitivity of the Antineutrino Probe for Reactor Core Monitoring

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This paper presents a feasibility study of the use of the detection of reactor-antineutrinos ($\overline{\nu}_e$) for non proliferation purpose. To proceed, we have started to study different reactor designs with our simulation tools. We use a package called MCNP Utility for Reactor Evolution (MURE), initially developed by CNRS/IN2P3 labs to study Generation IV reactors. The MURE package has been coupled to fission product beta decay nuclear databases for studying reactor antineutrino emission. This method is the only one able to predict the antineutrino emission from future reactor cores, which don't use the thermal fission of ^{235}U, ^{239}Pu and ^{241}Pu. It is also the only way to include off-equilibrium effects, due to neutron captures and time evolution of the fission product concentrations during a reactor cycle. We will present here the first predictions of antineutrino energy spectra from innovative reactor designs (Generation IV reactors). We will then discuss a summary of our results of non-proliferation scenarios involving the latter reactor designs, taking into account reactor physics constraints.

I. INTRODUCTION

During the last years, world-wide efforts have been devoted to the research and development of a potential innovative safeguards tool: reactor antineutrino detection. The idea was born in the seventies from particle physics experiments that reactor antineutrinos could not only been used as a particle source for fundamental studies, but also could be used as a monitoring tool, as their properties reflect the fuel composition of a reactor core. Current nuclear power plants (≈900 MWe) produce a $\overline{\nu}_e$ flux on the order of $10^{20}s^{-1}$ coming from the β^--decay of the fission products in the core. The $\overline{\nu}_e$ can be detected using the inverse β-decay process

$$\overline{\nu_e} + p \rightarrow n + e^+, \tag{1}$$

which has a very small cross-section ($\approx\ 10^{-43}cm^2$) depending on the energy of the incident $\overline{\nu}_e$, with a threshold of 1.8 MeV. The direct relationship between the antineutrino flux and energy spectrum at reactors and their power and fuel content has been demonstrated by reactor antineutrino experiments in the eighties and nineties. Recently "small" antineutrino detectors (less than 1t of liquid scintillator target) have been developed and have demonstrated a possible monitoring with a very simple detector placed at 25m from a PWR. Other detector design initiatives were born since then, and other safeguards-devoted experiments are taking data. In parallel, sophisticated simulations of reactors and their associated antineutrino flux have been developed to predict the antineutrino signature of fuel burnup and of a diversion. This prospective simulation work is complementary to the R&D of detection techniques. In order to determine how the antineutrino probe could be part of the future surveillance procedures, the characteristics of the antineutrino emission of all nuclear reactor designs have to be assessed. They will serve as well to determine the sensitivity goal of future antineutrino detectors devoted to reactor monitoring. The IAEA expressed its interest in the study of the performances of the antineutrino technique for safeguarding actual and future reactors, with emphasis on on-load reactors.

Current thermal neutron reactors use low enriched uranium fuel. ^{238}U usually represents more than 95% of the fuel and contributes to the production of power (7% to 10%) and builds up ^{239}Pu with the path given by

$$^{238}\text{U} + n \longrightarrow\ ^{239}\text{U} \xrightarrow{\beta}\ ^{239}\text{Np} \xrightarrow{\beta}\ ^{239}\text{Pu}. \tag{2}$$

Fig. 1 shows the increasing contribution of the plutonium isotopes to the production of power as a function of time (irradiation).

The characteristics of the fissions are different for ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu, as shown in Table I, and thus

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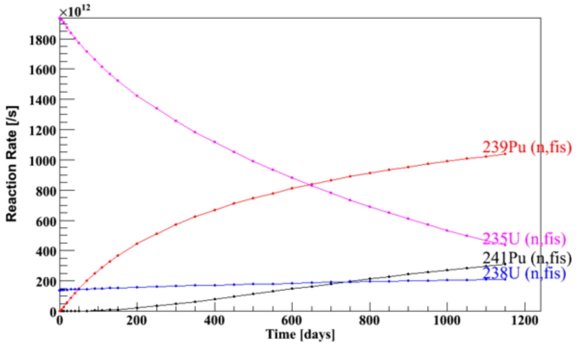

FIG. 1. Evolution in time of the contributions of the fissile nuclei in a typical 900 MWe reactor.

the increasing contributions of ^{239}Pu and ^{241}Pu fissions induce changes in the $\overline{\nu}_e$ flux and shape of spectrum. The discrepancy between the number and the mean energy of the $\overline{\nu}_e$ are mainly due to the differences in the fission product distributions of these nuclei. Indeed, the fission products are neutron-rich nuclei and join the valley of stability through β^- decay.

TABLE I. Differences in the ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu fissions given in Ref. [1] and a calculation of P. Huber and Th. Schwetz [2].

data per fission	^{235}U	^{238}U	^{239}Pu	^{241}Pu
released E (MeV)	201.7	205	210.0	212.4
$< N > \overline{\nu}_e$	5.56	6.69	5.09	5.89
($< N > \overline{\nu}_e$ with E >1.8 MeV)	1.92	2.28	1.45	1.83
$< E_{\overline{\nu}_e} >$ (MeV)	1.46	1.56	1.32	1.44

To sum up, as a fuel gets irradiated in time, its composition changes. It is especially the case for fissile nuclei which contributions evolve in time, and thus, so do both $\overline{\nu}_e$ flux and energy spectrum emitted by a nuclear power plant. The question is whether this property can be used for safeguards purpose. An $\overline{\nu}_e$-detector would be an unattended and tamper-proof tool able to remotely monitor the composition of the fuel incore. Our aim is to determine whether such a detector a cubic-meter in size would reach an accuracy sufficient to detect a "significant" diversion in a "timely" fashion. We assume that a significant quantity (SQ) [3] would be 8 kg of plutonium to be detected within 3 months.

II. SIMULATION TOOLS

In order to complete our study, we need to predict the evolution in time of the flux and energy spectrum of the $\overline{\nu}_e$ emitted by each type of reactor studied, and to evaluate the effect of a diversion of a SQ on the $\overline{\nu}_e$ flux and energy spectrum for each proliferating scenario. Our strategy for achieving this objective is presented in Fig. 2.

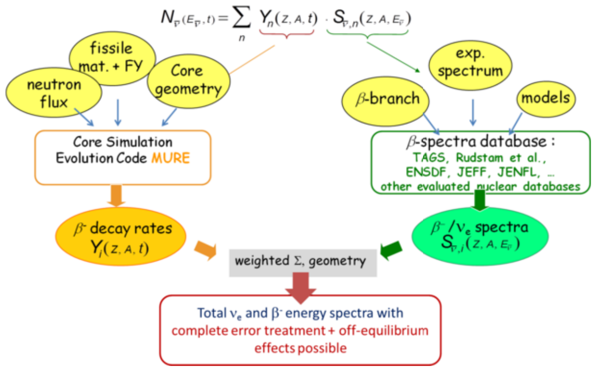

FIG. 2. Strategy of the simulation of the $\overline{\nu}_e$ spectra in the frame of our study.

To proceed to the left hand branch of Fig. 2, we need to develop a generic simulation tool. For this purpose, we use the MCNP Utility for Reactor Evolution (MURE) code. MURE has been developed by CNRS labs in order to study Gen. IV reactors and is available on the NEA website [4]. MURE automates the implementation of MCNP(X) [5] calculations and an evolution code that solves the Bateman equations. This simulation tool has allowed us to determine the reaction rates of each fissile nucleus and the production of their associated fission products leading to the composition of the fuel as a function of time. We also have access to the evolution in time of the multiplication factor (K_{eff} for a full core simulation, K_∞ in case of a infinite reactor simulation) of the core, and its delayed neutron fraction. We also have adapted this code for the construction of the $\overline{\nu}_e$ [6].

The systematic errors due to the uncertainties on the fission rates in a thermal reactor (PWR) have been evaluated by A. Onillon [7]. Since our calculation is relative (discrepancy between two scenarios for the same reactor) these errors on the fission rates were found to be 2.5% for ^{235}U, 5.5% for ^{239}Pu, 4.5% for ^{238}U and 7% for ^{241}Pu. We have evaluated the effect of these errors on the flux of $\overline{\nu}_e$ detected. We took the maximum error on ^{235}U and ^{239}Pu contributions and compensated them by ^{238}U and ^{241}Pu contributions: the influence on the $\overline{\nu}_e$ flux is of 0.8%.

Knowing the evolution in time of each fission product, we can proceed to the right hand branch of Fig. 2, and model the $\overline{\nu}_e$ spectrum emitted by these nuclei. Our approach is to build the spectrum by summing of the contribution of each nucleus [8, 9]. Currently, there is no proper estimate on the uncertainties associated with this summation method, and we will use a 10% bin to bin uncertainty as a first step [10].

This complete tool allows us to investigate various diversion scenarios. We present in this article scenarios for a PBR (Pebble Bed Reactor) and a sodium-cooled FBR (Fast Breeder Reactor). These reactors are Gen IV