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DESIGN OF TEX-MOX CRITICAL EXPERIMENTS VARYING NEUTRON SPECTRUM

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ABSTRACT

In the International Criticality Safety Benchmark Evaluation Project (ICSBEP) only a limited amount of critical experiments representative of MOX fuel with low moderation is present. This paper aims at describing the design of a set of critical experiments with varying neutron spectra that should contribute to nuclear data validation for this kind of configurations.

Complementary to the few existing experiments in the ICSBEP, a series of independent experiments can be performed on the PLANET machine at NCERC (National Criticality Experiments Research Center) using the uranium-plutonium fuel plates. Due to the decay heat emitted by the fuel plates, a dedicated thermal-mechanical design of the assembly has been defined to fit all the experimental constraints: weight, limited temperature and temperature gradient within the assembly, minimal effect on neutronics and others. The 5 critical configurations designs are described in this paper.

KEYWORDS

Validation, critical experiments, MOX fuel, epithermal, TEX

1. INTRODUCTION

The need for thermal/epithermal and intermediate energy range (0.625 eV to 100 keV) critical benchmarks is an established international criticality safety data need [1]. One of the configurations that needs validation of a mixed uranium-plutonium system in the intermediate energy range is encountered in the MOX fuel fabrication process. During this stage, uranium and plutonium oxides can be found in several configurations. Initially, the composition is a 100 % PuO₂ powder, which is then mixed with UO₂ powder to a maximal content of 30 % PuO₂ by weight. In the next steps, the content of PuO₂ is reduced below 12.5 %. Some hydrogenated materials could be added during the mixing that have to be taken into account for criticality safety studies. The maximum water equivalent in oxide powders considered in safety demonstrations is 3 % for normal operation and 5 % for accidental conditions, which results in epithermal neutron energy configurations. One of the goals of TEX-MOX (Thermal/Epithermal eXperiments) experiments is to contribute to cover the domain of the UO₂ and PuO₂ powder mixtures (11 % - 30 % PuO₂ content) with a varying isotopic content of ²⁴⁰Pu (5 % - 25 %) and different moderation levels representative of water contents between 0 % and 5 %.

In general, very few integral experiments are found in ICSBEP Handbook in the intermediate energy range. Recently, PMM-002 benchmarks using plutonium fuel plates were added providing a high sensitivity for the plutonium 239 cross sections in the intermediate energy range. This work focuses on the design of the TEX-MOX experiments, which in addition to Pu²³⁹ sensitivity are also sensitive to U²³⁸ and Pu²⁴⁰ isotopes. These experiments correspond to IER (Integral Experimental Request)-296 of U.S. Department of Energy Nuclear Criticality Safety Program (NCSP), that could be performed at National Criticality Experiments Research Center (NCERC) in the next years.

2. EXPERIMENTAL DESIGNS

The general experimental setup consists of a stack of layers: each layer is composed of fuel plates positioned on an aluminum plate and a moderator plate with a variable thickness, located between the fuel layers. The used fuel plates are mainly the PUMN (Pu-U-Mo plates manufactured by Numec Corporation) plates and to a lower extend PUMH (Pu-U-Mo plates manufactured by Numec with High ²⁴⁰Pu content) plates.

First, a multi-parametric configuration was optimized in order to maximize the number of fissions in the intermediate energy range [2]. This goal being the major challenge, the general experimental configuration parameters were fixed based on this optimized configuration. Thus, the fuel footprint size (layer of 9x3 PUMN-6" plates) and the materials used (aluminum and high-density polyethylene (abbreviated PE)) were chosen to be used for the TEX-MOX series of experiments. Indeed, a series of five experiments is planned to be performed, where the 4 other experiments are variations of the optimized intermediate spectra configuration. Preliminary designs were described in a CED-1 NCSP report [3].

The PUMN plates characteristics are described in Table I. The intermediate experimental assembly may need up to 30 fuel layers to be critical. The PUMN plates available at NCERC have different lengths, and the number of the 6"-long available plates is not sufficient to fill all fuel layers. Thus, it is foreseen to use 15 layers using 27 6"-long PUMN plates, as shown in Figure 1, and 15 layers mixing 9 6"-long, 9 4"-long and 9 8"-long PUMN plates that correspond to the same fuel footprint. Current design models are based on 6"-long fuel plates only, and thus the compositions of 4" and 8" long fuel plates were not yet calculated for the expected execution year of the experiment.

Table I. Fuel plates characteristics calculated for summer 2025

	PUMN			PUMH
	4"	6"	8"	6"
TOTAL Fuel mass [g]	437.7	668.9	900.7	669.5
Pu/TOTAL [% w]		27.7%		32.7%
Am/TOTAL [% w]		0.4%		1.6%
Pu239/Pu [% w]		87.9%		70.8%
Pu240/Pu [% w]		11.7%		27.2%
Pu241/Pu [% w]		0.1%		0.5%
U/TOTAL [% w]		69.3%		63.1%
U235/U [% w]		0.3%		0.3%
U238/U [% w]		99.7%		99.7%
Mo/TOTAL [% w]		2.5%		2.5%
Decay Power [W]	0.56	0.85	1.14	2.06

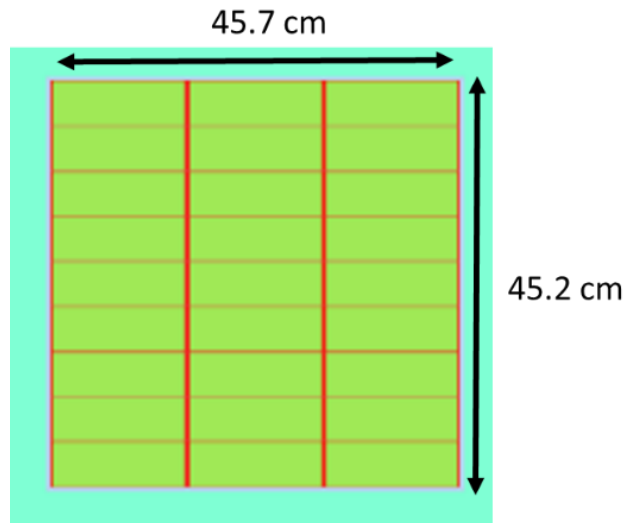


Figure 1. Cross section view of the TEX-MOX configuration fuel layer (9 x 3) using 6"-long PUMN fuel plates (15.24 cm x 5.02 cm x 0.69 cm)

When the general design parameters were fixed based on neutronic analysis, a more realistic design was considered that integrates thermal-mechanical experimental constraints which is described in the following. The intermediate spectrum configuration was used to optimize the thermal-mechanical design, since it represents the most challenging case, requiring around 30 fuel layers, and leading thus to a maximal decay heat source, power density and fuel mass, among other configurations.

2.1. Thermal-mechanical design

The experiment is executed by stacking fuel layers on the movable and the fixed parts of the PLANET machine. The constraints considered for the thermal-mechanical design are based on material properties limits, weight limits of the PLANET machine and neutronics considerations to limit uncertainties of the future benchmark. They were defined as follows:

- Simple geometry (preference for rectangles)
- Maximal temperature in contact with PE < 80°C
- Thermal gradient within the critical configuration < 15°C
- Duration of the closed configuration < 10 min
- Duration of the separated (two parts) configuration ~days/week
- Minimize the deformation of materials
- No other materials in proximity of the assembly
- Ensure alignment/positioning of the fuel plates and other elements
- Reduce and measure horizontal and vertical gaps
- Lower movable part weight < 400 kg.

The weight of a fuel layer was calculated to be around 30 kg. Thus, the weight limit on the movable part of the PLANET machine leads to split the configuration into a “10 fuel layers” stack for the movable lower part and a “20 fuel layers” stack for the upper fixed part. This subcritical configuration, separated in 10 and 20 fuel layers stacks, can stay for several days, whereas the critical configuration of 30 fuel layers, where the two parts are in contact, will not exceed 10 min. Hence, the temperature increase during this time is considered as negligible, far from the thermal equilibrium. Only the 20 fuel layers stack is studied for thermal considerations.

The design of the aluminum structure to support the fuel layer is presented in Figure 2. It consists of a thick aluminum sheet with a thickness of 0.7 - 1 cm, and an aluminum frame, that helps the fuel plates

centering and avoid contact between the heat source and the polyethylene. The aluminum frame and the aluminum bars, placed between the fuel plates, are thicker than the fuel plates to support the weight of the whole fuel assembly stack. The polyethylene frame is put around the aluminum frame and it plays the role of the radial reflector in the assembly. The vertical cut of the fuel layer is presented in Figure 3.

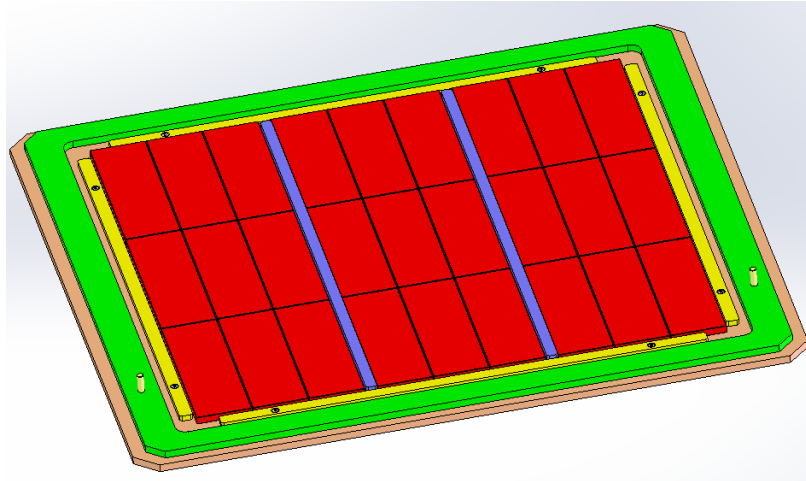


Figure 2. 27 fuel plates in red disposed on the aluminum tray in orange, surrounded by aluminum frame in yellow, with aluminum bars between the fuel plates in blue, and polyethylene frame in green

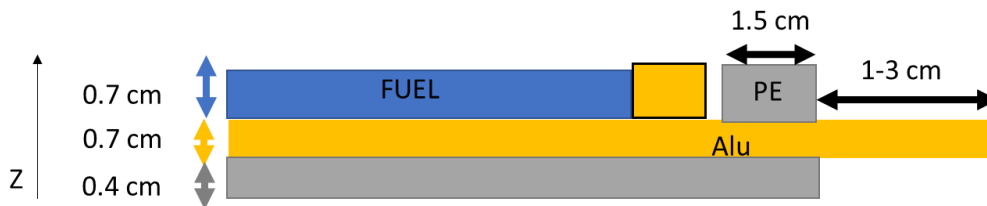


Figure 3. Vertical cut of one fuel layer stack corner scheme not to scale with fuel plates in blue, aluminum in yellow and polyethylene in grey

2.2. Thermal calculations

Based on the decay heat evaluation for the time of a possible execution date in 2025, as presented in Table I, a fuel layer leads to approximately 23 Watt. Thermal calculations were performed with the generic CFD solver library CALIF3S (for Components Adaptive Library for Fluid Flow Simulations), an in-house IRSN software released under an open-source license [4]. The model is built using the geometry described in Figure 3. Perfect contact is assumed between all parts. The fuel stack is constituted of 20 superimposed fuel plates surrounded by aluminum and polyethylene that lies over an aluminum plate, that models the fixed table of the PLANET machine. A symmetry is assumed with respect to planes normal to the Ox and Oy axes and containing the stack mass center. Consequently, only a quarter of the structure was computed. The thermophysical properties of aluminum, polyethylene and plutonium are supposed to be constant and are detailed in Table II. The heat flux from the structure surface to the fluid is the sum of convection and radiation heat fluxes. The heat exchange coefficient due to natural convection h depends on the orientation of each surface, and thus its value varies from 1.5 - 4 W/(m².K). The accuracy of these values has been verified by computing the external flow in dedicated simulations.

The radiative heat flux is calculated using the emissivity coefficient provided in Table II, that leads to a heat exchange coefficient of 6.4 W/(m².K) for polyethylene, which appears to be the driving cooling mechanism in this configuration.

Table II. Thermophysical properties used in the CFD modelling

	aluminum	polyethylene	plutonium
Thermal conductivity [W/(m.K)]	167	0.4	6.74
Heat capacity [J/(kg.K)]	896	900	130
Density [kg/m ³]	2700	940	19850
Emissivity	0.1	0.95	-

The thermal equilibrium is reached after approximately one day, as shown in Figure 4. The temperature increase distribution within the aluminum and polyethylene is shown in Figure 5. The temperatures provided in those plots illustrates the temperature increase considering the room temperature at 0 K. To obtain the expected temperature in the configuration, first one have to convert Kelvin in Celsius and add the room temperature to those values. For instance, if the room temperature is 13°C or 20°C, the maximal PE temperature is expected to be 63°C or 70°C respectively.

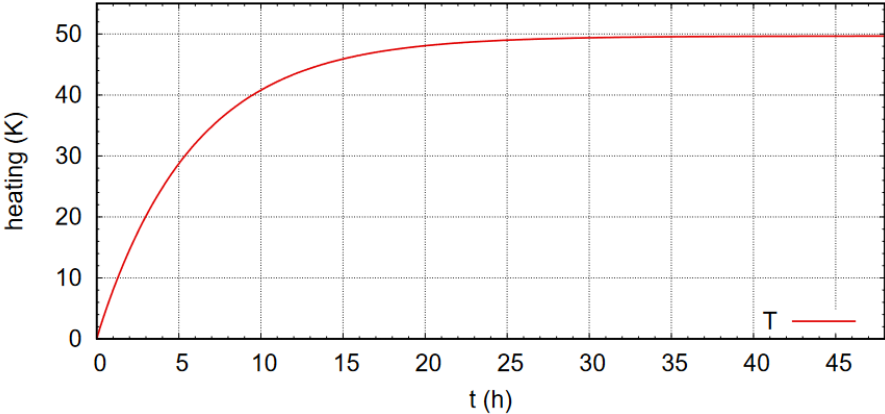


Figure 4. Maximal temperature increase as a function of time

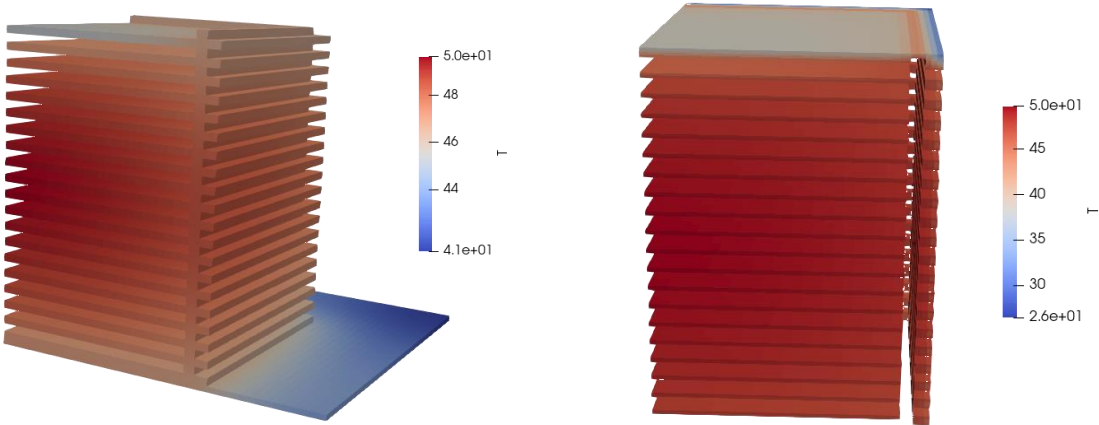


Figure 5. Temperature increase distribution for aluminum parts on the left and for PE parts on the right in Kelvin.

Based on the observed temperature increase, it was decided to propose an active cooling system to have a good quality experimental benchmark. Indeed, the benchmark temperature should be at 20°C, and in order to reduce the bias and associated uncertainties due to the average temperature change, the experiment should be as close as possible to this temperature. Besides, a low temperature gradient <15°C within the experimental assembly is suitable. This is due to the motivation to keep the critical benchmark simple, without thermal gradient, that requests to estimate the bias and associated uncertainties due to the temperature gradient removal on the k_{eff} . Additionally, to the gradient shown in Figure 5, one must consider that the 10 fuel layers stack will reach another equilibrium temperature, lower than the one presented here, which can lead to an important temperature gradient over the whole critical assembly configuration. To reach those goals an active cooling system will allow to adjust the temperature of the assembly and to decrease the thermal gradient within it.

Nevertheless, for safe execution of this experiment, it must be ensured that in case of cooling system failure, the polyethylene temperature for softening or melting, around 85°C and 130°C respectively for high density polyethylene, will not be reached.

2.3. Cooling system

The proposed cooling system is based on the air sucking within the aluminum supporting plate through air channels as illustrated in Figure 6. Each aluminum plate will be fabricated through screwing of two initial plates, and connected to tubes, that lead to collectors. Those elements are composed exclusively in aluminum. The collectors can then be connected via flexible pipes to the air pump. A sketch of the possible stack on the PLANET machine using those cooling plates for 2 out of 3 fuel layers is shown in Figure 7. Other fuel layers rely on initially described aluminum supporting plate.

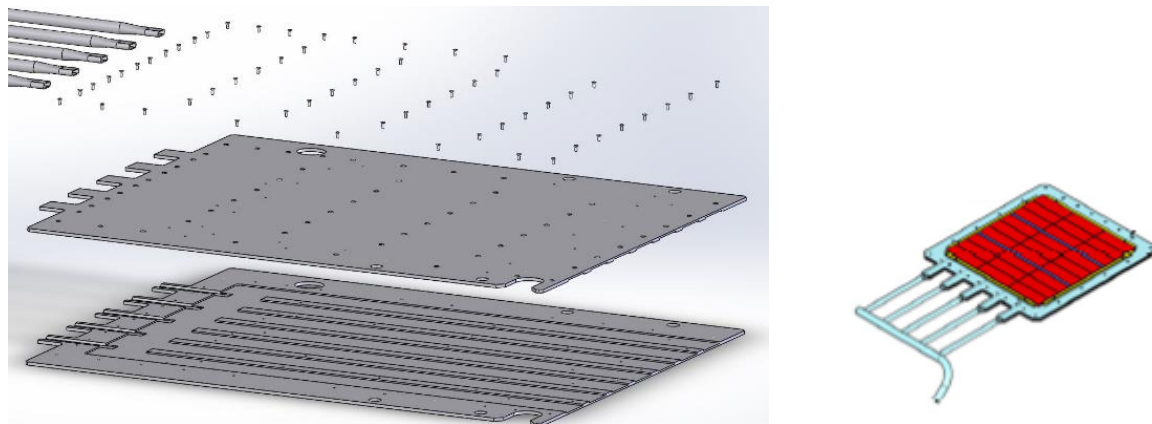


Figure 6. Exploded view of the aluminum supporting plate with cooling channels on the left based on two initial plates that were screwed together and connected to tubes, connection to the aluminum tubes and collectors on the right.

The exact number of cooling plates that will be used in the critical configuration are not yet determined and will be the result of ongoing studies. Indeed, the idea is to find the optimal number of cooling plates that compromise between keeping the execution of the experiment simple and keeping the average temperature and temperature gradient low. It will also be verified that the cooling plates with its external structure do not deteriorate the passive cooling mechanism, that need to be considered for the safety demonstration of these experiments.

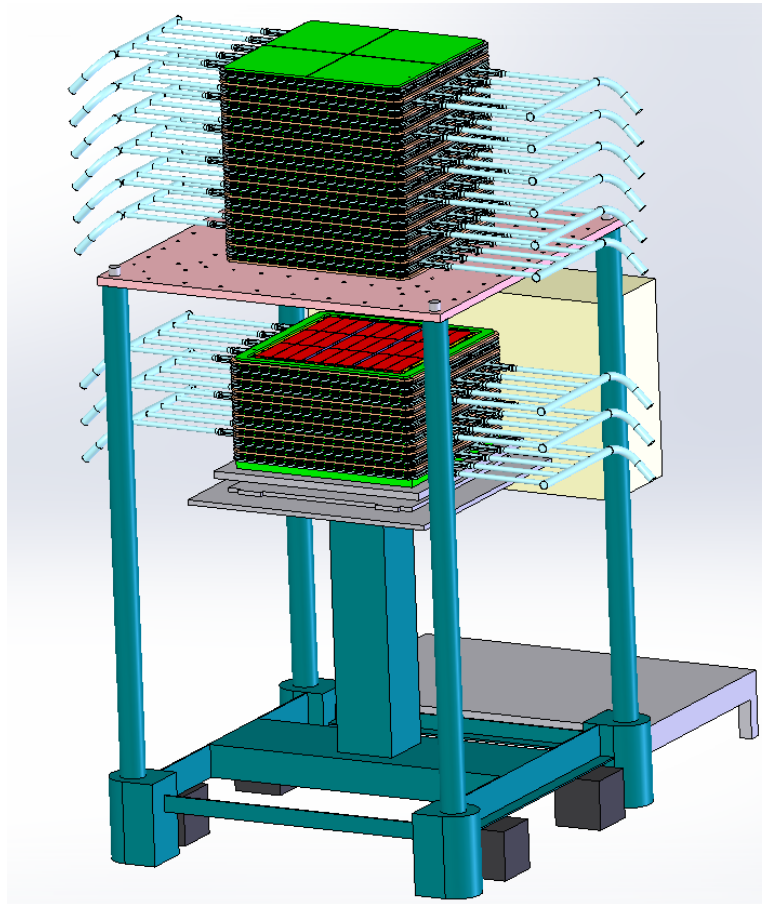


Figure 7. Sketch of the PLANET machine containing the configuration separated in the fixed and moving part with the cooling plates for 2 out of 3 fuel layers.

3. VARYING NEUTRONIC SPECTRUM DESIGNS

The 5 experiments that will be proposed for execution at NCERC are being optimized regarding several aspects. The goal is to propose experiments that will meet critical benchmarks needs for specific application cases, validate nuclear data in energy ranges where validation is lacking and confirm the experimental approach. Furthermore, these experiments are expected to cross validate the experimental bias and uncertainty estimations in the whole series. For instance, benchmarks in fast and thermal spectrum with mixed uranium-plutonium systems exist in ICSBEP handbook. The execution of new experiments in fast and thermal spectrum may allow to confirm the previously observed bias with new, expected higher quality, experiments. Indeed, many old ZPR/ZPPR experiments used a homogeneous model which validity is questionable.

The planned experiments are listed below:

- I. TEX-MOX thermal energy configuration
- II. TEX-MOX intermediate energy high Pu²⁴⁰ content configuration
- III. TEX-MOX intermediate energy configuration (maximal intermediate fission rates)
- IV. TEX-MOX intermediate energy configuration (to be optimized)
- V. TEX-MOX fast energy configuration

The experiment I, sensitive to thermal energy neutrons, will have a thick moderator of PE, and the total stack may stay below 10 fuel layers for the critical configuration.

The experiment II will use PUMH fuel plates in the central fuel layers to increase the sensitivity to Pu^{240} capture cross section. The characteristics of this fuel plates are detailed in Table 1. The resulting k_{eff} sensitivity to Pu^{240} capture cross section is increased to -0.046 in comparison to -0.032 in the configuration III, as displayed in Figure 8.

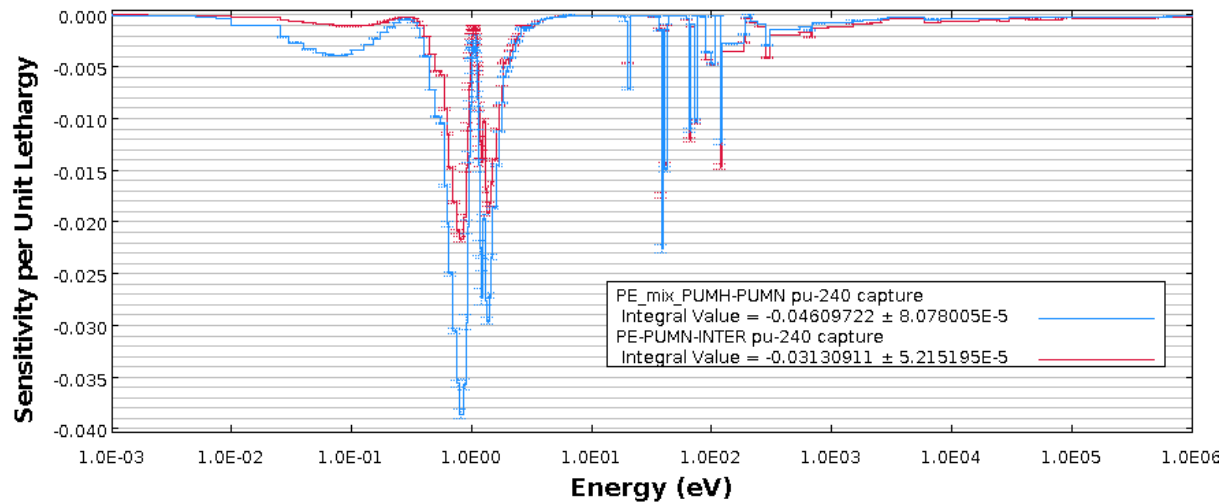


Figure 8. Comparison of k_{eff} sensitivity profiles of the Pu^{240} capture cross section for the configuration III, in blue, and II, in red

The configuration III resulted of multi-parametric optimization to maximize the intermediate energy fission rates, and shows very similar neutron energy profile, as shown in Figure 9, with an application case corresponding to a stage in the French MOX fuel fabrication process.

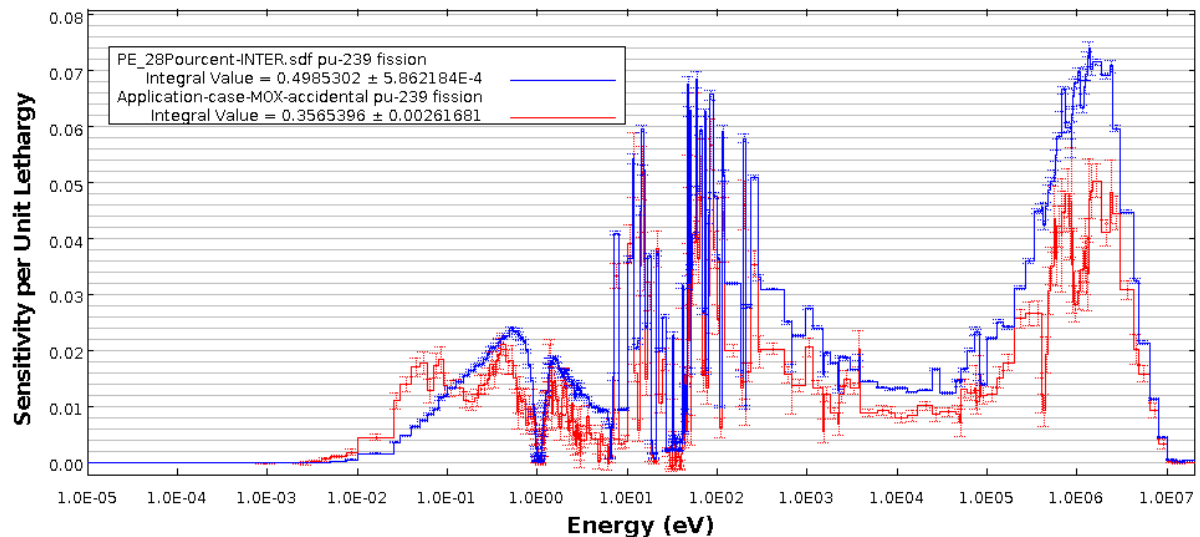


Figure 9. Comparison of k_{eff} sensitivity profiles of the Pu^{239} fission cross section for the configuration III, in blue, and an application case in red

Two options are considered for the configuration IV. The first is to perform an experiment very similar to configuration III, but at higher temperature (reducing the number of cooling plates). The goal is to use it to contribute to the nuclear data temperature effect validation and to confirm the experimental bias and uncertainty calculations of this series. Indeed, all TEX-MOX experiments will not be performed at precisely 20°C, and thus a bias due to temperature effect must be evaluated with the associated uncertainty. To be confident in this evaluation, a dedicated experiment will allow to verify experimentally the temperature effect by comparing the experiment III and IV, that will be very similar besides the temperature of the configurations. Additionally, this high temperature experiment might provide rare validation data of the temperature effect, which may be useful beyond the criticality safety applications. The second option for the configuration IV is to vary the thickness of the polyethylene moderator between the fuel layers to shift the neutron spectrum, to have a complementary experiment, since the intermediate energy range that is lacking in experiments is very broad (0.625 eV to 100 keV).

The configuration V will have no PE sheets in between the fuel layers. The aluminum supporting plates will be put on the top of each other. The PE or aluminum will be used as radial reflector, to minimize neutronics effects from the elements in the room around the experimental setup.

4. CONCLUSIONS

The main goal of the TEX-MOX experiments is to provide benchmarks representative of the configurations with mixed uranium-plutonium systems and low moderation. The proposed design is based on the usage of ZPR/ZPPR fuel plates with a significant Am²⁴¹ and Pu²⁴⁰ contents, that leads to a significant temperature increase due to the decay heat. To execute those experiments at an average temperature close to 20°C, as suited for a benchmark, an active cooling system is proposed. The idea is to cool the fuel supporting plates, that has the advantage to have a small impact on neutronics. CFD simulations of a non-cooled assembly were performed to ensure that with a cooling system failure the experimental subcritical configuration remains safe.

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