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DESIGN METHODOLOGY FOR FUEL DEBRIS EXPERIMENT IN THE NEW STACY FACILITY

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ABSTRACT

The new criticality experiments facility STACY will be able to contribute to the validation of criticality calculations related to the fuel debris. The experimental core design is in progress in the frame of JAEA/IRSN collaboration. This paper presents the method applied to optimize the design of core configurations of the new STACY to measure the criticality characteristics of pseudo fuel debris focused on Molten Core Concrete Interaction (MCCI) debris. To ensure that a core configuration is relevant for code validation, it is important to evaluate the reactivity worth of the main isotopes and the k_{eff} sensitivity to their cross sections. If the sensitivities profiles are similar to those of the configuration to be validated, it is potentially feasible to provide relevant feedback on its nuclear data. In the case of MCCI debris described in this study, silicon is the nucleus that has the highest k_{eff} sensitivity in the concrete. Therefore, some parameters of the core configuration, as for example the lattice pitch or the core dimensions, were adjusted using optimization algorithm to research efficiently the optimal core configurations to obtain high sensitivity of silicon capture cross section. This method allows exploring a large space of possibilities by limiting the number of calculations. Two examples of designs tested using this approach are presented in this paper. The first study was performed on a simple square core configuration with ideal conditions. In the second study, the core was divided in two zones to investigate the interest of having both an experimental zone and a driver zone. Based on these results, realistic series of experiments for fuel debris in the new STACY could be defined to obtain an interesting feedback for the MCCI.

KEY WORDS

Critical Experiment, New STACY facility, Criticality safety of fuel debris

1. INTRODUCTION

In the post-Fukushima prospect, Japan Atomic Energy Agency (JAEA) intends to re-open its Static Experiment Critical Facility (STACY) [1]. The objective of the intended research using the new STACY is to establish an improved database on criticality safety. In particular, this database is expected to assist in the removal of fuel debris from the Fukushima Daiichi Nuclear Power Plant. The new STACY got its installation permission from Nuclear Regulation Authority (NRA) of Japan on 31th January 2018 and modifications are undergoing.

The new STACY is a light water moderated critical assembly with UO₂ rods (see Figure 1) and it will be able to use pseudo fuel debris, meaning specific rods composed of UO₂ powder mixed with iron, concrete and other materials included in fuel debris. The enrichment in ²³⁵U of the 900 UO₂ rods, which have been manufactured recently, and UO₂ powder are both 4.98 wt.%. Table I shows some specifications of the new STACY.

Some specific rods will be manufactured to simulate “fuel debris” like the corium core mixed with concrete. A small fabrication facility will be constructed in order to manufacture pseudo fuel debris samples using uranium oxide, iron, zircaloy, concrete, and other inside/outside materials of commercial reactor vessels. Several methods have been considered for the loading of these irradiation samples; one of them consists in loading the core with fuel rods using an openable sheath tube having the same shape and material as the fuel rods. In this study, this loading method was adopted to optimize the core configuration of the new STACY.

Moderation ratio expressed by Eq. 1 is an important parameter in the new STACY experiments. One will be able to change slightly this value by adjusting the pitches of a lattice (interval between rods).

$$\frac{V_m}{V_f} = \frac{\text{Volume of moderator (H}_2\text{O)}}{\text{Volume of fuel (UO}_2\text{)}} \quad (1)$$

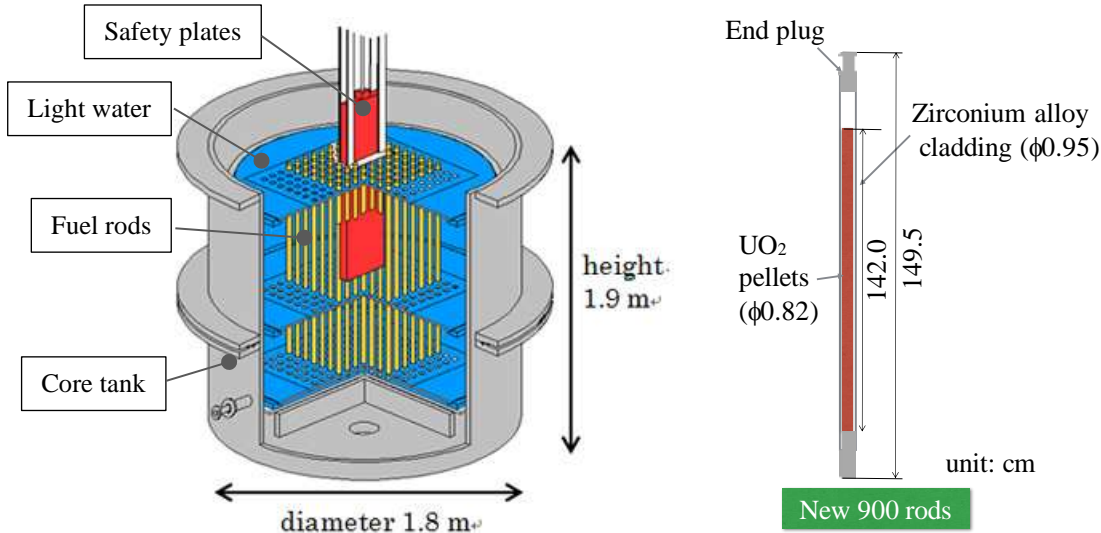


Figure 1. Overview of the new STACY and its UO₂ fuel rod element.

Table I. Specifications of the new STACY (permitted ranges).

Maximum number of fuel rods loading	< 900
Fuel composition	UO ₂ (< 10 wt.% enriched ²³⁵ U)
Critical water height	40 – 140 cm
Temperature of light water moderator	< 70 °C
Thermal power	< 200 W
Material of cladding	Zircaloy (E110 type)
Effective fuel height (stack height of UO ₂ pellets)	142 cm
Diameter of UO ₂ fuel pellet	0.82 cm
Outer diameter of cladding	0.95 cm

2. CONFIGURATIONS OF INTEREST FOR THE CORE DESIGN

The objective of the fuel debris experiments is to evaluate the effect of molten-core-concrete-interaction (MCCI) product to facilitate criticality risk assessments during retrieval from the reactors. The MCCI product is composed of a mixture of fuel, concrete, and others (iron, zircaloy...), and could have a significant impact for the criticality safety on retrieval works.

Criticality characteristics of MCCI depend on the concrete content, therefore the target of this study was decided to focus on UO₂-concrete mixtures. As concrete compositions in the fuel debris of the Fukushima reactors are not exactly known, the concrete composition used in this presented work was based on the reference [2] with a concrete density of 2.3 g/cm³. These hypotheses are significant; however, the objective of this paper is to present the design method that could be applied later to other compositions.

Before starting the design of the experiments, one should define the application cases of interest. Figure 2 shows one of the application cases considered in criticality safety studies. It consists of a lattice of fuel debris spheres composed of UO_2 (5 wt.% enriched ^{235}U) mixed with concrete with a content equal to 60 %, surrounded by water. The spheres are located in a face-centered cubic (FCC) lattice. The interval between these spheres is adjusted so that $V_m/V_f = 1.0$, and the effective diameter of the debris spheres lattice is adjusted to obtain $k_{\text{eff}} = 1$.

Sensitivity analyses were performed using MCNP6.1 [3] with JENDL-4.0 library [4]. The k_{eff} sensitivity (S) to the cross section (σ) is the relative effect on the k_{eff} caused by a cross section's perturbation of the reaction i of the nucleus j .

$$S_{ij} = \frac{\partial k \cdot \sigma_{ij}}{k \cdot \partial \sigma_{ij}} \quad (2)$$

These analyses are used to estimate the influence of an isotope on the k_{eff} , and more precisely, the reactions and energy domains that have an impact on the k_{eff} . If one reaction's sensitivity to a cross section of an isotope is high, it means the reaction's cross section has a significant weight on the k_{eff} of the studied configuration, and that it is potentially feasible to provide relevant feedback on nuclear data assessments.

For the studied application cases, ^{28}Si , ^{39}K , ^{56}Fe and ^{40}Ca capture cross sections have the greater integral sensitivity values (see Figure 3). The sensitivity profiles of ^{28}Si , ^{39}K , and ^{56}Fe have larger peak in thermal neutron energy than in fast neutron energy. On the other hand, ^{40}Ca has larger peak in fast neutron energy slightly offset from the peak of ^{28}Si . Therefore, ^{28}Si and ^{40}Ca were selected as the target isotopes to make the preliminary core configurations of the new STACY to validate MCCI debris.

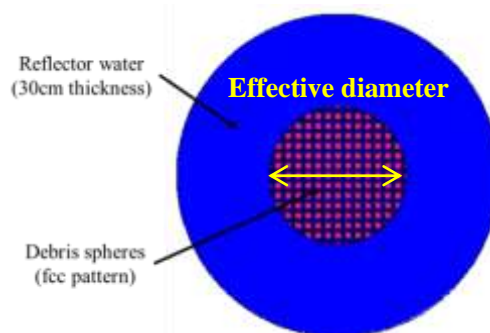


Figure 2. Example of the application cases studied.

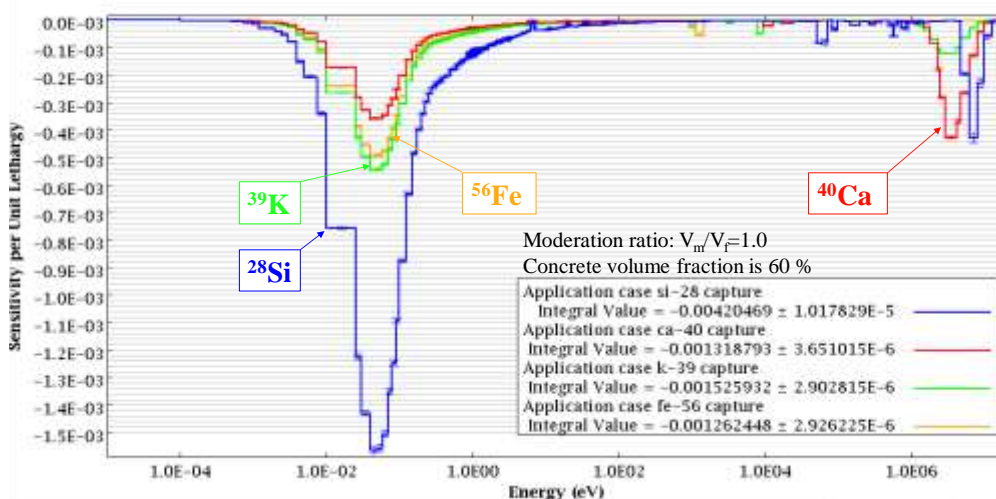


Figure 3. k_{eff} sensitivities to capture cross sections of ^{28}Si , ^{39}K , ^{56}Fe , and ^{40}Ca for the application case.

3. OPTIMISATION ALGORITHMS

3.1 PROMETHEE and EC-EGO

In order to optimize the design of core configurations, meaning to maximise k_{eff} sensitivity to ^{28}Si and ^{40}Ca cross section, the IRSN PROMETHEE workbench [5] was used. It is not only a launcher tool, but it also allows parameterizing the input files for many calculation codes and it embeds various algorithms, like “Efficient Global Optimization (EGO),” which was used to define the numerical experiments. This Bayesian optimization algorithm relies on a stochastic response surface with interactive raising knowledge in the interesting zones of the input parameters space to reach the minimal/maximal values of the parameters of interest. However, the EGO algorithm is basically designed to search for a minimal/maximal value, without considering any constraint on a code system. Therefore, in this study, Equality Constraint Efficient Global Optimization (EC-EGO) algorithm derived from EGO, was used to maximize the sensitivity coefficients to ^{28}Si and ^{40}Ca capture cross sections while keeping the core configuration critical [6].

Using PROMETHEE with EC-EGO algorithm allows performing several optimizations with various input parameters as for example, the lattice pitch or the concrete volume fraction in the fuel debris sample rods. This approach allows exploring a large space of possibilities by limiting the number of calculations.

3.2 Uniform Distribution Algorithm

During the optimization calculations, an arrangement of the fuel rods and the pseudo fuel debris rods is made automatically with a simple R-function developed for this purpose. The goal of this function is to obtain a uniform distribution of the pseudo fuel debris rods in the square lattice. This function sample numbers between 0 and 1 with Latin Hyper Square method (LHS). The sample size is equal to the lattice dimension and the aim is to maximize the distance between each point. The function takes into account the proportion of pseudo fuel debris rods in the lattice. It scans the grid and checks in each box if there is one point of the sample (i.e. pseudo fuel debris rod) or not (see Figure 4). It is translated in the matrix which is then used to write the lattice frame index of MCNP input file.

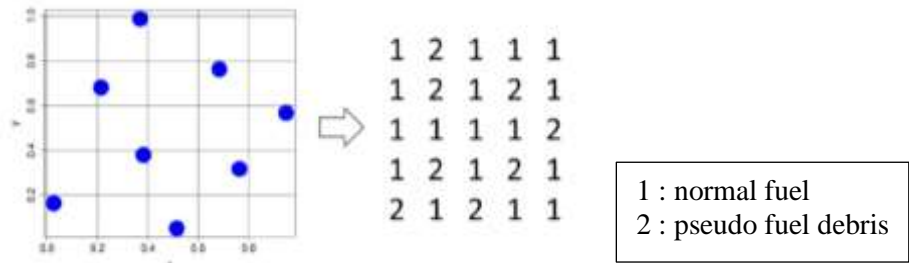


Figure 4. Illustration of one sampling (blue points on the left) and the associated matrix (on the right) that define the pseudo fuel debris rod coordinates in the lattice frame.

4. COMMON PARAMETERS AND TARGET OF THE STUDIES

The target value for the optimization, the constraints, the varying parameters, and their variation ranges were defined at first. In this series, the pseudo fuel debris rods have the same shape and the same length as the normal fuel rod. They will be inserted in the core by replacing the normal fuel rods. The water level is fixed at 130 cm.

As discussed previously, in the MCCI application cases, ^{28}Si capture cross section is the main contributor to the k_{eff} sensitivity in the concrete. Therefore, the design of the core configurations was first drawn to maximize the absolute integral value of k_{eff} sensitivities to ^{28}Si ($S_{-^{28}\text{Si}}$) and then focus on the optimization of the ^{40}Ca capture cross section ($S_{-^{40}\text{Ca}}$). The proposed core configurations must be critical, so a value of k_{eff} slightly higher than 1 is required in order to considered an eventual calculation bias, the water level can be reduced to adjust criticality.

Some parameters were defined to optimize the core configurations. One of them is the concrete volume fraction (CVF) in the pseudo fuel debris, which is defined by the Eq 3.

$$CVF = \frac{V_c}{V_{UO_2} + V_c} \quad (3)$$

where V_c and V_{UO_2} are respectively the concrete and UO_2 volumes. If a value of CVF equal to 0, there is no concrete in the pseudo fuel debris rod. On the contrary, for a value of CVF equal to 1, the pseudo fuel debris sample rod is composed only of concrete. The ratio of the number of pseudo fuel debris over the total number of rods (w) is also a key parameter.

$$w = \frac{N_{fd}}{N_{fd} + N_f} \quad (4)$$

where N_{fd} and N_f are respectively the number of fuel debris sample rods and the number of fuel rods in the experimental zone, which corresponds to the central area in the experimental core configuration, where the pseudo fuel debris rods were inserted. The external zone is a driver zone composed of only normal fuel rods to achieve criticality. The number of fuel rods in driver zone was not taken into account in w value. The w ratio is used by the algorithm to arrange the patterns of the different types of rods mentioned in 3.2.

Another important parameter is the pitch (P) between the rods. The variation range of P is from 1.0 to 3.0 cm. This parameter has an impact on the neutron spectrum, because it changes the moderation ratio (V_m/V_f). The sizes of each zone are also parametrized.

5. STUDIES OF SIMPLE CYLINDRICAL CORE CONFIGURATIONS

A Simple cylindrical core configuration was optimized to test the method using the different algorithms (EC-EGO and uniformed distribution of sample) and to obtain the maximum sensitivity values for an ideal core condition. An example of the calculation model is illustrated in Figure 5. The core size (R), the pitch size (P), w and CVF were considered as parameters. Their variation ranges are defined in Table II. CVF is considered as a discontinuous parameter, so the optimization is performed for each of the 5 defined values: 0.01, 0.25, 0.50, 0.75, and 0.99.

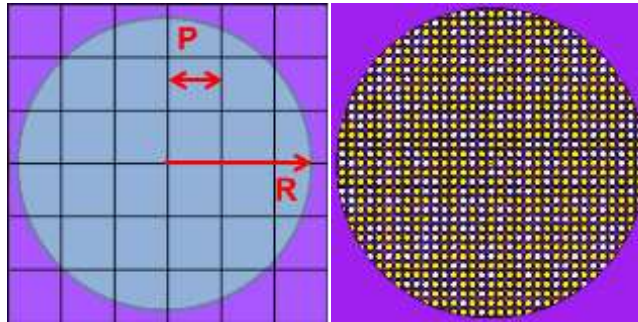


Figure 5. Illustration of design approached (on the left), and core configuration example (on the right).

Table II. Parameters variation ranges.

Parameters	R [cm]	P [cm]	w	CVF
Minimum	3	1	0.1	0.01
Maximum	31	3	0.9	0.99

The optimization process leads to a maximum S_{-28Si} value of $2.2 \cdot 10^{-2}$. It was obtained in the case of $R \approx 31$, $P \approx 1.0$, $w > 0.87$, and $CVF = 0.99$. From this result, one can conclude that to obtain larger sensitivity, it is necessary to increase CVF values in the pseudo fuel debris sample rods as much as possible and increase the value of w . The smaller lattice pitch is suitable to obtain larger sensitivity because more fuel rods and more pseudo fuel debris rod are able to be loaded. However, the core configuration using combinations of large CVF

values and large w values could not achieve the criticality. These results were obtained with unrealistic core configurations, so additional optimizations were performed.

6. STUDIES OF SQUARE CORE CONFIGURATIONS

6.1 Simple Square Zone Optimization

To confirm the interest of 100 % concrete rods (CVF = 1.0), the simple square zone optimizations were tested. In fact, it will not be possible to fabricate the pseudo fuel debris pellets with high CVF value such as CVF = 0.9. On the other hand, it is easy and economical to manufacture 100 % concrete rods. But it is important to evaluate if it is possible to obtain equivalent results with 100 % concrete rods or with pseudo fuel debris rods.

In this study, the simple square core configuration (P = 1.27) had a 13 x 13 rods experimental zone in the center. 85 pseudo fuel debris rods were inserted to the experimental zone (see Figure 6). CVF values were changing from 0.1, 0.25, 0.5, 0.75, 0.99, to 1.00¹. Other parameters were fixed, except the numbers of driver fuel rods that were adjusted to achieve criticality.

The sensitivities of capture reactions of ²⁸Si and ⁴⁰Ca increased with the CVF value and the sensitivity profiles were similar (example Figure 7). On the other hand, the sensitivities of fission reactions of ²³⁵U and ²³⁸U, and capture reaction of ²³⁸U were not changed significantly. Based on these results, it was considered possible to evaluate the criticality characteristics of the MCCI product using samples with only concrete (CVF = 1) and normal fuel rods. This method will allow reducing technical constraints and cost for making large number of pseudo fuel debris rods. Therefore, for subsequent optimization and evaluation, the pseudo fuel debris rods with CVF = 1 were basically used.

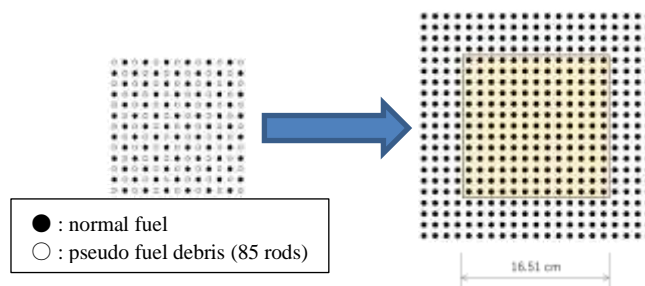


Figure 6. Illustration of the simple square core configuration with a 13 x 13 experimental zone.

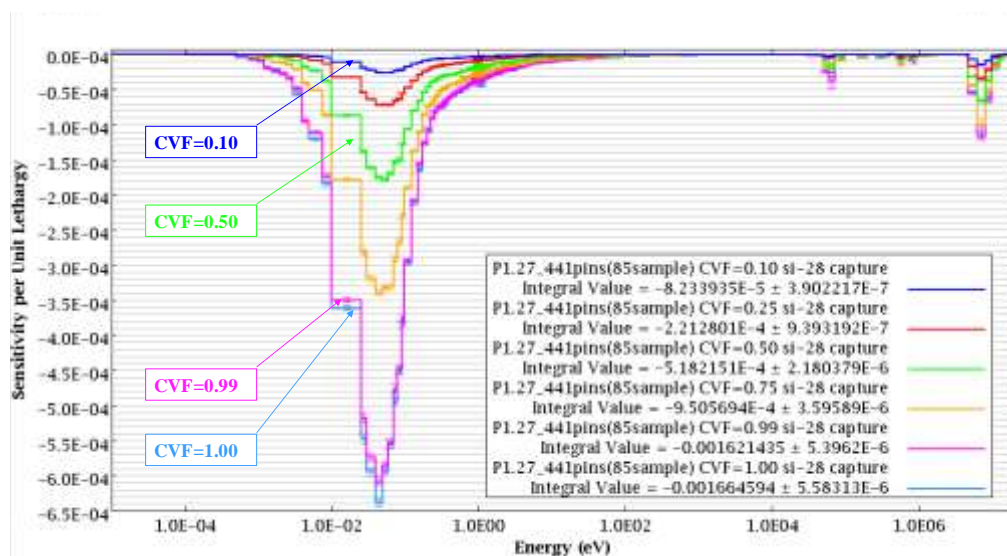


Figure 7. Comparison of the profiles of sensitivity $S_{^{28}\text{Si}}$ with various CVF values.

¹ The exact value of use for the following calculations is CVF = 0.99999

6.2 Multi-Zones Optimization Approach

Multi-zones optimization was considered to get larger value on k_{eff} sensitivity for ^{28}Si capture cross sections. This optimization model was made by two or three zones that have different pitches and sizes. In this paper, the results of two zones optimization are described. An overview of the calculation model is shown in Figure 8. The optimization is performed on the pitches (P1 and P2), zone sizes (D1 and D2) and w . In these parameters, D1 was arranged to be a multiple of P1. R-function mentioned in 3.2 was used to make the uniform patterns of the pseudo fuel debris sample rods in experimental zone, with fixed random seed.

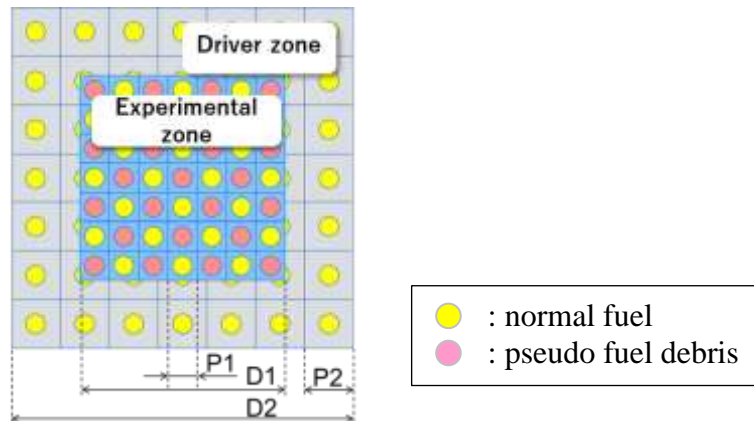


Figure 8. Principle scheme of the calculation model for two zones optimization.

The optimization was performed over 1,100 MCNP calculations using PROMETHEE. Figure 9 shows results for all combination of parameters by pair plot. From these results, three core configurations were selected by their pitches (P1 = 1.00, 1.15, and 1.50) and sizes of the experimental zones (25 x 25, 21 x 21, and 15 x 15) as shown in Table III. These configurations satisfy other requirements for the new STACY, such as core averaged moderation ratio (0.9 - 11.0).

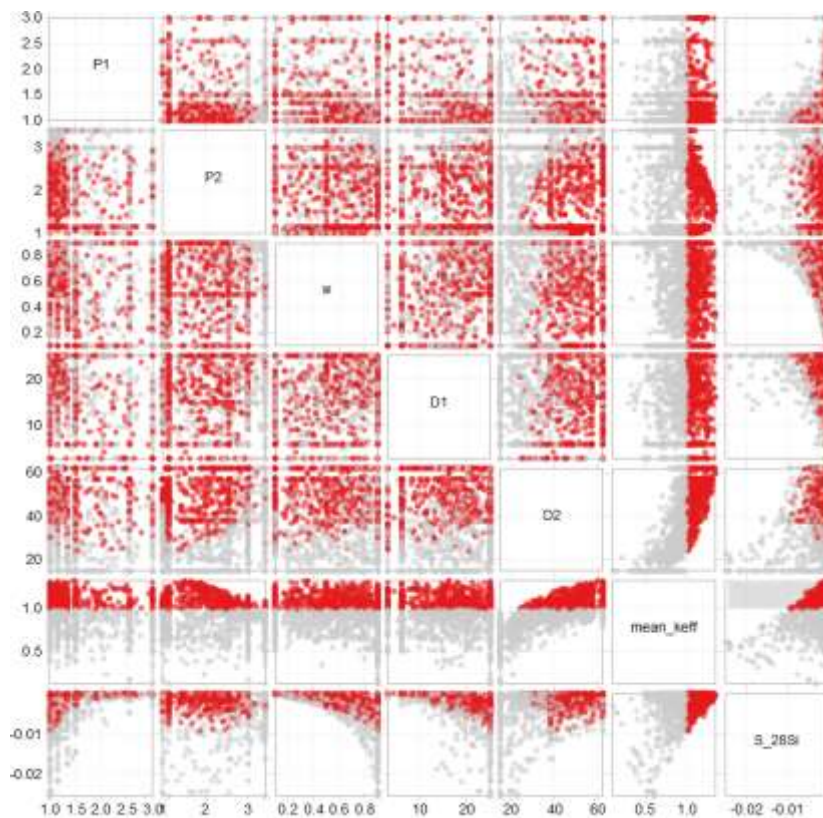


Figure 9. Pair plot of the two zones optimization with selection of cases with $k_{\text{eff}} > 1$.

Another key point is that these core configurations have very complicated insertion patterns of the pseudo fuel debris rods in the experimental zones, because they were determined randomly by R-function. So, it should be important to simplify the insertion patterns to reduce the risk of mistake by the operators. Therefore, some insertion patterns were tested and compared with original patterns. The examples of the original and simplified insertion patterns are shown in Figure 10. These regular insertion patterns were performed manually using the previous results and the number of the driver fuel rods were adjusted individually to obtained k_{eff} values close to 1.

Table III. Selection of the optimization results.

Experimental (exp.) zone	P1 [cm]	Number of pseudo fuel debris rods (CVF = 1)	P2 [cm]	D2 [cm]	k_{eff} ($\sigma < 0.00072$)	$S_{^{28}\text{Si}}$ (^{28}Si capture)	$S_{^{40}\text{Ca}}$ (^{40}Ca capture)
25 x 25	1.00	563 (w = 0.90)	2.41	54.16	1.07684	$-6.84 \cdot 10^{-3}$	$-1.80 \cdot 10^{-3}$
21 x 21	1.15	397 (w = 0.90)	2.13	47.66	1.08773	$-5.27 \cdot 10^{-3}$	$-1.38 \cdot 10^{-3}$
15 x 15	1.50	144 (w = 0.64)	1.09	32.73	1.02314	$-3.43 \cdot 10^{-3}$	$-8.98 \cdot 10^{-4}$

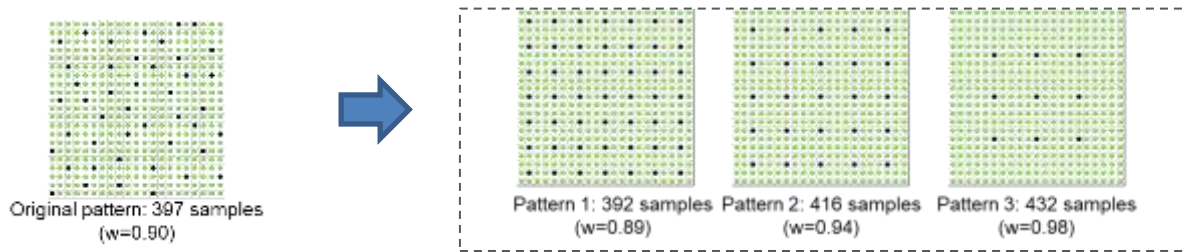


Figure 10. Examples of simplified insertion patterns in the experimental zone. (Green dot: pseudo fuel debris, Black dot: normal fuel)

The integral sensitivities of ^{28}Si and ^{40}Ca capture reactions in each insertion pattern of the pseudo fuel debris rods are shown in Figure 11 for the three selected core configurations. The comparison of the optimization results highlights that the sensitivity does not always increase with the number of the pseudo fuel debris sample rods. Indeed, when the number of the pseudo fuel debris rods is very high, the neutron flux in the experimental zone decreases, therefore the k_{eff} sensitivities decrease. Inversely, if the number of the pseudo fuel debris rods is too small, there is not enough concrete in the experimental zone and the k_{eff} sensitivities decrease. For the majority of configurations, the k_{eff} sensitivity obtained by the optimization is close to the best values and it is possible to have equivalent results with simple insertion patterns.

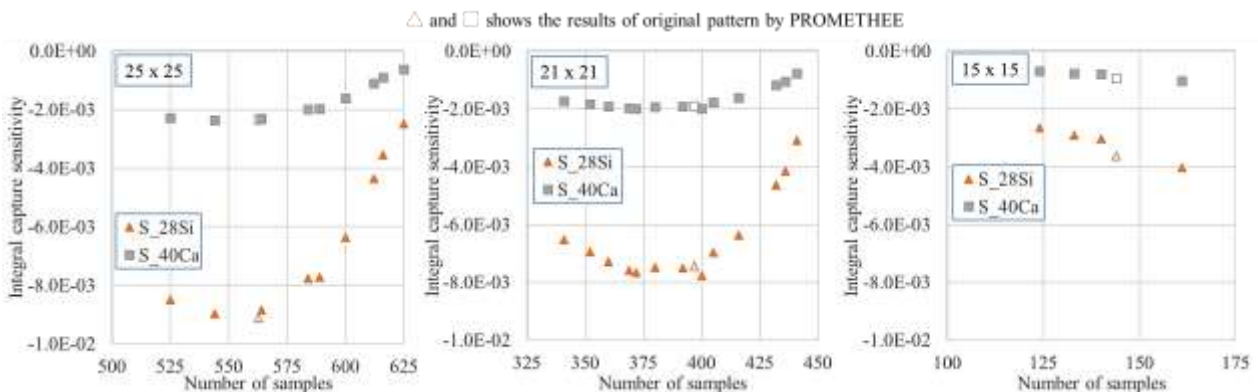
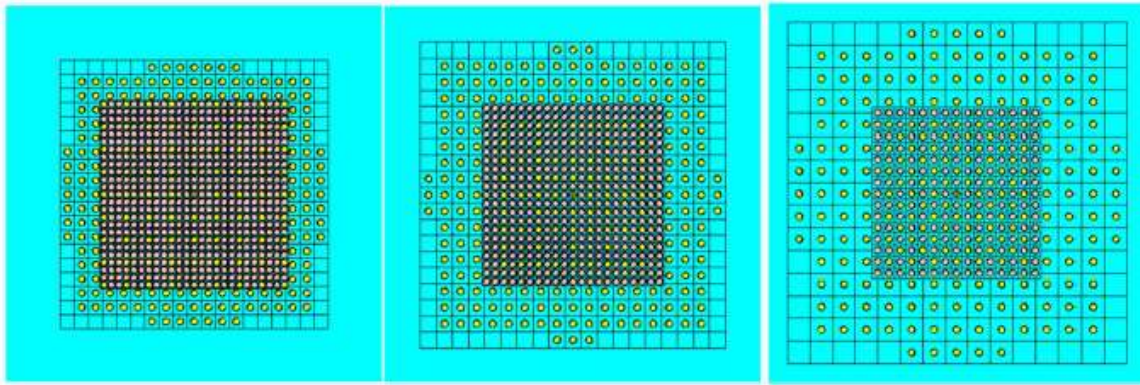


Figure 11. Optimization results for three core configurations and additional cases with different number of pseudo fuel rods.

Finally, three core configurations having different moderation ratio were selected. The overviews of these configurations are shown in Figure 12 and Table IV. In each case, the maximum sensitivities $S_{^{28}\text{Si}}$ and $S_{^{40}\text{Ca}}$

obtained are respectively $-9.0 \cdot 10^{-3}$, $-7.7 \cdot 10^{-3}$, $-3.2 \cdot 10^{-3}$, and $-2.4 \cdot 10^{-3}$, $-2.0 \cdot 10^{-3}$, $-8.2 \cdot 10^{-4}$. The $S_{^{28}\text{Si}}$ values are smaller (between 41% to 15%) than that of the unrealistic cylindrical core configurations presented in 5.



(25 x 25)

(21 x 21)

(15 x 15)

Figure 12. Overviews of the final optimized core configurations for the new STACY.

Table IV. Final optimized core configurations.

Exp. zone	k_{eff} ($\sigma < 0.00031$)	Number of pseudo fuel debris rods (CVF = 1)	Number of fuel rods (total)	Pitch of exp. zone [cm]	V_m/V_f in exp. zone	Pitch of driver zone [cm]	$S_{^{28}\text{Si}}$ (^{28}Si capture)	$S_{^{40}\text{Ca}}$ (^{40}Ca capture)
25 x 25	1.00420	544 ($w = 0.87$)	277	1.00	0.55	2.41	$-9.0 \cdot 10^{-3}$	$-2.4 \cdot 10^{-3}$
21 x 21	1.00298	372 ($w = 0.84$)	249	1.15	1.16	2.13	$-7.7 \cdot 10^{-3}$	$-2.0 \cdot 10^{-3}$
15 x 15	1.00482	140 ($w = 0.62$)	225	1.50	2.92	3.00	$-3.2 \cdot 10^{-3}$	$-8.2 \cdot 10^{-4}$

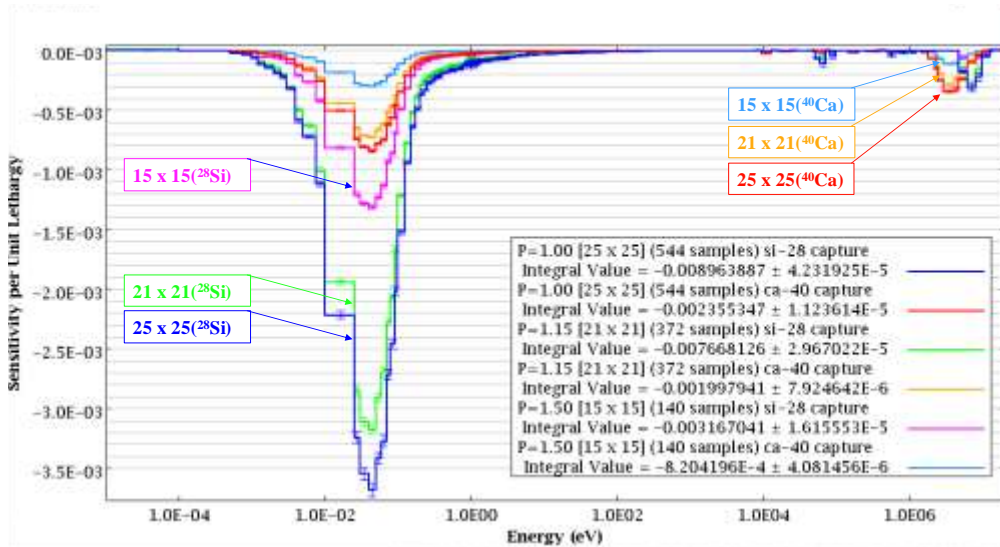


Figure 13. Sensitivity profiles of ^{28}Si and ^{40}Ca capture reaction in the optimized core configurations.

The moderation ratios in each test region are 0.55, 1.16, and 2.92. The sensitivities profiles of ^{28}Si and ^{40}Ca capture cross sections show that there is no spectrum effect (see Figure 13). Figure 13 was not normalized, but the peak positions and the shape of the sensitivity profiles of ^{28}Si capture reaction are almost same in each core configuration. And the same observation is made for the sensitivity ^{40}Ca . So, difference of neutron spectra between the center and the outer of the experimental zone in function of the pitch seems to have negligible

effect on the $S_{28\text{Si}}$ sensitivity. About 550 of the concrete sample rods and different lattice grids for two zones core configurations should be prepared before starting the series of experiments for measurement of criticality characteristics of MCCI product fuel debris.

7. CONCLUSION

In the frame of Fukushima Daichi fuel debris retrieval, Japan Atomic Energy Agency (JAEA) intends to re-open its Static Experiment Critical Facility (STACY). The objective of the intended researches for the new STACY is to establish an improved database on criticality safety. The first core configurations of the new STACY facility to measure the criticality characteristics of MCCI type fuel debris were designed in this study.

The design method applied to define preliminary configurations dedicated to concrete study, is based on the optimization of k_{eff} sensitivity to the cross section using the IRSN PROMETHEE tool. For the concrete composition considered in the presented work, ^{28}Si is one of the main sensitivity contributors of the concrete. By consequences, the design was mainly focused on the sensitivity of the capture cross sections of the ^{28}Si , but ^{40}Ca was also studied. To obtain the maximum integral sensitivity and to reduce the calculation cost while investigating a large space of possibilities, the method used optimization algorithms. At the end of this study, it is proposed that pseudo fuel debris rods will be composed only of concrete. To respect some experimental constraints, the preliminary configurations were designed considering two zones: an experimental zone and a driver zone, where the pseudo fuel debris rods were inserted. Finally, after some adjustments of the optimized configurations for experimental issues, three core configurations with different moderation ratios were retained in this study.

However, some other issues have to be discussed before starting the experiments. First of all, these preliminary configurations will need to be refined in future studies to take into account all of the new STACY constraints. The concrete composition is also a parameter to consider with attention. To have experiments adapted to the diversity of possible concretes, experiments for different concrete compositions could be considered. These compositions could be based on the samples taken from Fukushima Daiichi NPP. Finally, it is necessary to evaluate the experimental uncertainties prior the experiments and to make experimental plans to reduce these uncertainties as much as possible. These issues should be studied in near future.

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