Development of Domestic Fresh Fuel Identification Algorithm through Comparative Analysis of Nuclear Fuel Signatures

Gayeon Ha [a], Hana Seo [b], Yujeong Choi [b], Gyunyoung Heo [a*]
[a] *Department of Nuclear Engineering, Kyung Hee University, Gyeonggi-do, South Korea*
[b] *Korea Institute of Nuclear Nonproliferation and Control, Daejeon, South Korea*
[*] *Corresponding author: gheo@khu.ac.kr*

1. Introduction

The purpose of nuclear forensics is to establish an international DB (Database) to identify the characteristics, origin and distribution processes of unidentified nuclear materials, and to prevent nuclear terrorism. In order to do this, it is necessary to build a nuclear forensics libraries for each country, and analysis of the basis for the identification of nuclear materials and comparative analysis with the database is required.

In this study, we have developed and algorithm that can identify whether the discovered fuel pellets are fresh nuclear fuel for domestic nuclear power plants by limiting the unidentified nuclear material to the form of nuclear fuel pellets. For this purpose, signatures such as shape and density, and the characteristics analysis of domestic nuclear fuel quality control have been preceded. Through this, DB for nuclear fuel signatures was constructed and an algorithm was developed to identify the domestic nuclear fuel using comparative analysis with the domestic fuel DB.

2. Methods and Results

2.1. Analysis of the Characteristics Distribution of Domestic Nuclear Fuel Quality Control

In order to develop a domestic fresh nuclear fuel identification algorithm, it is necessary to investigate the nuclear fuel signatures and to analyze the distribution characteristics of the domestic nuclear fuel quality control factor. In the previous study [1], the analysis results of feasibility of fresh nuclear fuel characteristics as signatures were obtained.

Table Ⅰ: Feasibility analysis of fresh nuclear fuel characteristics as signatures [1]

Characteristic Parameters		Availability*		Identification Target				Possibility of damage
		Single	Combination	Reactor type	Country	Manufacturer	Fabrication process	
Physical	Pellet Length	-	O	O	-	O	-	O
	Pellet Diameter	-	O	O	-	O	-	O
	Density	O	-	O	-	-	O	X
	Geometric combination	O	-	-	-	O	-	O
Chemical	Composition	-	O	O	-	-	O	X
	Enrichment	-	O	O	-	-	-	X
	O/U ratio	-	O	-	O	O	O	X
	$^{18}O/^{16}O$ ratio	O	-	-	O	-	-	X
	Impurities	O	-	-	-	O	O	△
Microstructure	Grain size	-	O	-	-	-	O	X

* Single: Working alone, Combination: Multiple parameters required

2.1.1. Physical Signatures

Physical signatures include pellet shape, diameter, length, density, surface roughness and grain size. The geometric combination such as dish and chamfer can be an important signatures in identifying the manufacturer of the fuel, but the pellet is susceptible to breakage, so it is necessary to consider the possibility of damage.

Since the physical characteristics, such as diameter and length, are fuel specification, the value as signatures may be low. But the degree of process variation may be different even if the same specification is satisfied, so it is considered as basic signatures.

Fig. 1. Shows the distribution of physical signatures for domestic PWR, domestic CANDU, and some foreign nuclear fuel from the literature survey [2]. There are many differences between the domestic PWR and the domestic CANDU for Pellet diameter and length, but the distribution of domestic PWR and the foreign fuel are very similar. However, density, surface roughness and grain size are different in three cases.

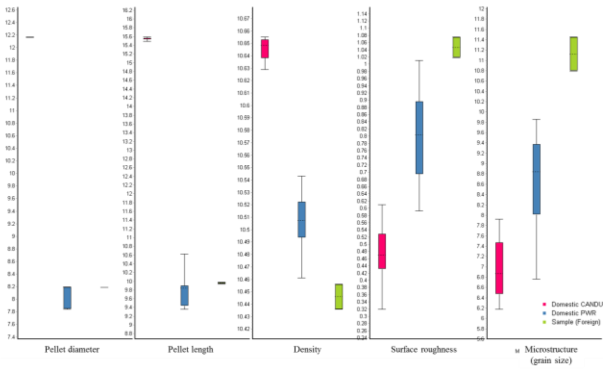

Fig. 1. Comparison of physical signatures distribution

2.1.2. Chemical Signatures

Chemical signatures include enrichment, O/U ratio, and O-isotope ratio. Among them, O-isotope ratio is not a characteristic factor for the quality control of domestic nuclear fuel. Therefore, it is difficult to build a DB, so it is excluded from the analysis. Fig. 2. Shows the distribution of chemical signatures for domestic PWR, domestic CANDU, and some foreign nuclear fuel from the literature survey [2]. Here, enrichment is confirmed as a signature that can distinguish between PWR and

CANDU. However, it was difficult to find a large difference in O/U ratio for the three cases.

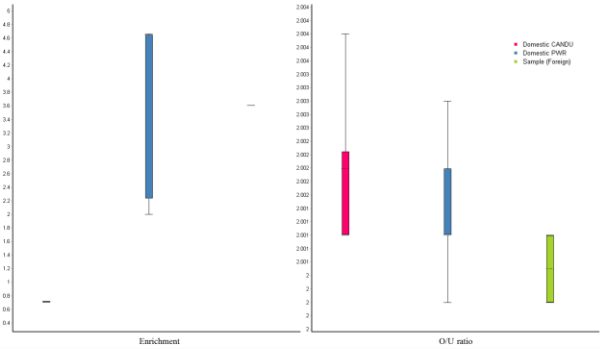

Fig. 2. Comparison of chemical signatures distribution

2.1.3. Element (Impurities) Signatures

According to the previous research [1], impurities have a large difference according to the manufacturing process, but it is difficult to find an element that can identify the manufacturer and the country because the information in the open literature is limited. In addition, there are more than 20 types of impurity elements in the DB, which is difficult in the comparative analysis process. In the case of impurities, it is difficult to obtain data by nuclear fuel manufacturers. However, if information about elements possessed only by manufacturers and countries is secured, they can be considered as a stronger signatures.

Therefore, Principal Components Analysis (PCA) [3] was used to generate new variables (principal components) reflecting the overall characteristics of high-order impurity data and to use them for comparison. PCA is a multivariate statistical analysis method that is typically used for dimension reduction. By converting the given data into an axis with the maximum variance, it reduces the dimension and extracts features of the data. Fig. 3. shows the result of PCA on domestic nuclear fuel impurity data. Dimensional reduction allowed us to visually identify groups for domestic PWR and domestic CANDU nuclear fuel.

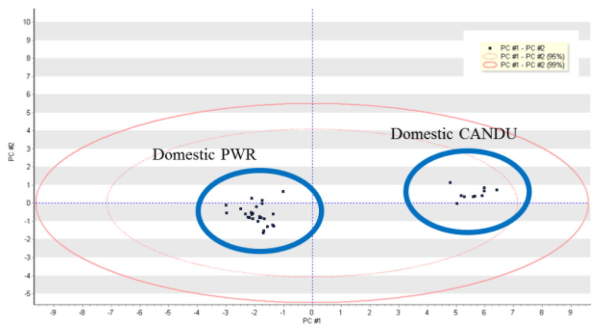

Fig. 3. Dimensional reduction using PCA

2.2. Development of Domestic Nuclear Fuel Identification Algorithm

In this study, we developed an algorithm that can identify domestic nuclear fuel using various comparative analysis methods with DB which is constructed through the distribution analysis of nuclear fuel characteristics. Fig. 4. shows the overall identification algorithm. The developed algorithm is implemented as ECMiner [4], a specialized data mining software.

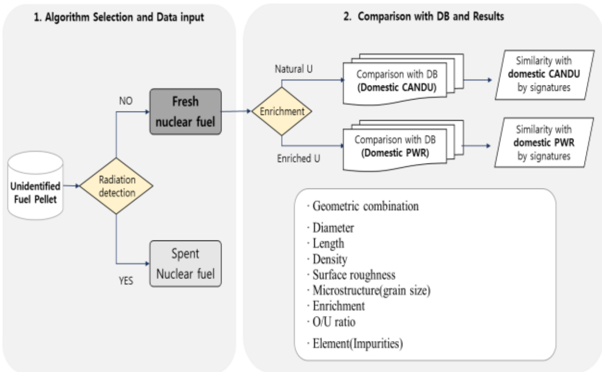

Fig. 4. Nuclear fuel identification algorithm

2.2.1. Algorithm Selection and Data Input

It is possible to distinguish between fresh nuclear fuel and spent fuel initially through the radiation detection on unidentified nuclear fuel pellet. Previous studies [5] have developed a classification algorithm capable of inversely estimating the nuclear material characteristics (burnup, cooling time, enrichment, reactor type) from the nuclide information in the spent nuclear fuel. Initial conditional statements on radiation detection enable linkage of the fresh fuel and spent fuel algorithm. If no radiation is detected in the unidentified fuel, it is determined to be fresh fuel and applied to the fresh nuclear fuel identification algorithm.

In the next step, each signature information is given as an input value for fresh fuel identification, and the similarity is evaluated through comparison with DB.

2.2.2. Comparison with DB and Results

Depending on the fuel enrichment, the nuclear fuel can be divided into natural and enriched uranium. If the unidentified fuel is natural uranium, it is compared with the domestic CANDU DB, and as a result, the similarity with domestic CANDU for each signature is output. On the other hand, if enriched uranium, it outputs the similarity with domestic PWR as a result of comparison with domestic PWR DB. As shown in Fig. 5., the signatures are divided into three parts according to the distribution characteristics, and the comparison with the domestic DB is made possible by using different similarity evaluation methods.

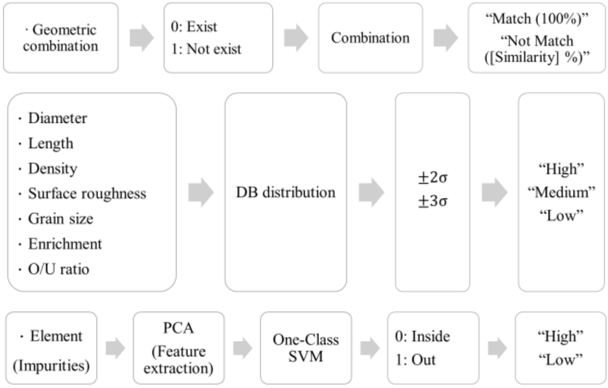

Fig. 5. Similarity evaluation algorithm by signatures

The first part is a comparison algorithm for geometric combinations. It is evaluated by comparing the presence or absence of each structure such as dish and chamfer without numerical comparison. The similarity of geometric combinations can be expressed by the total number of matching structures among the total number of comparison structures. If they are completely matched, "Match (100%)" is output. However, if they do not match, "Not Match" and "the similarity calculation result" are simultaneously output.

The second part contains continuous signatures such as pellet diameter, length, and so on. The similarity is evaluated according to where the unidentified fuel is located in the DB distribution for each signatures. As shown in Fig. 6., when each signature is assumed to be a normal distribution, the similarity was classified into three levels (High/Medium/Low) based on 2σ and 3σ of the distribution.

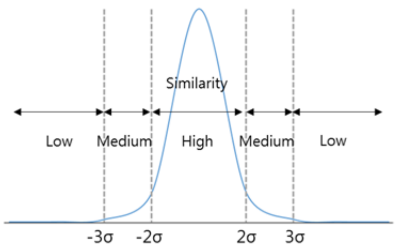

Fig. 6. Similarity to continuous signatures

Finally, one-class SVM (one-class Support Vector Machine) technique [3] was used to evaluate the similarity of impurity signatures. SVM, which is known as the best classification technique in terms of accuracy, maps the data space to a higher dimensional feature space using kernel functions and finds an optimal classification hyperplane boundary. As shown in Fig. 7., one-class SVM using SVM creates the classification boundary by grouping the data into one group, and confirms whether or not the new data is included in the cluster. At this time, data outside the boundary are regarded as outliers.

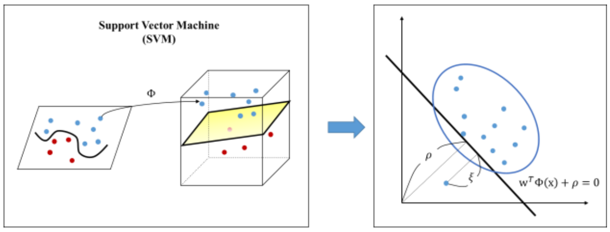

Fig. 7. Principles of one-class SVM

As shown in Fig. 3., impurity data newly extracted by PCA is reduced to low dimension and used as learning data of one-class SVM. Domestic nuclear fuel data are clustered into two groups (domestic PWR and domestic CANDU), respectively, to determine that outlier is not domestic nuclear fuel. That is, if the unidentified fuel belongs to a group, it is judged to be similar to domestic fuel and outputs "High" and if it does not belong, it is judged not to be similar and outputs "Low".

3. Conclusions

In this study, we have developed an algorithm to identify domestic nuclear fuel. In order to verify the identification of domestic fresh fuels, a verification process of algorithms is required and various domestic and foreign fuel data are required. However, there is a limit that the disclosure of nuclear fuel information of each country is limited. Therefore, there were difficulties in verifying the data because comparable foreign data could not be obtained in this study. Once the data is collected, we expect to be able to verify the algorithms developed in this study. Finally, based on the developed algorithm, the similarity evaluation results by the signatures can be presented and related experts can comprehensively determine whether the unidentified fuel is domestic one.

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