Hyperspectral Imaging based Characterization and Identification of Sintered UO_2 Fuel Pellets

J. Zabalza, A. J. Parker, M. Bandala, P. Murray, S. Marshall, X. Ma, C. J. Taylor, M. Joyce, D. Hutchinson, P. Stirzaker, and D. Eaves

***Abstract*— Hyperspectral Imaging (HSI) is a well-established technology able to capture the same spatial scene or image in hundreds of different wavelengths across the electromagnetic spectrum, covering not only the visible but also the shortwave infrared range (1000-2500nm), potentially revealing information otherwise invisible to the human eye. In this work, we explored whether HSI technology can be used for the fast-non-invasive characterization and identification of sintered UO_2 fuel pellets. Preliminary experiments included the imaging of the pellets, revealing their spectral responses. These show promising features that could be used for their identification, where two different groups of pellets, pure and doped, seem to be easily recognized based on their spectral response. The experiments included a pixel-wise classification map generated via the Spectral Angle Mapper (SAM) technique in which the pure and doped pellets are successfully identified.**

***Index Terms*—Characterization, hyperspectral imaging, identification, nuclear fuel pellets, spectral angle mapper.**

I. Introduction

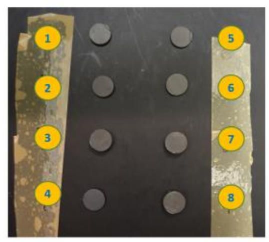
The evaluation of sintered UO_2 fuel pellets via fast non-intrusive techniques has great potential within the nuclear industry for a number of key activities including quality inspection, anomaly detection or enrichment analysis [1-2]. The automated characterization and identification of nuclear fuel pellets with different compositions is a niche of particular interest, where some techniques including X-ray diffraction, X-ray photoelectron spectroscopy and micro Raman have been proposed in the literature [3]. However, Hyperspectral Imaging (HSI) technology, able to provide spectral information across a spatial domain, has barely been researched in this context.

HSI is a technology able to capture an image in hundreds of different wavelengths across the electromagnetic spectrum, covering not only the visible but also the Shortwave Infrared region (SWIR, 1000-2500nm). Working across the SWIR region, this technology is able to capture information otherwise invisible to the human eye, providing the (potentially unique) spectral response or signature of different materials in nature.

In this work, HSI was used to capture the inherent spectral response of sintered UO_2 fuel pellets, revealing potential features from which discrimination between different types of pellets (in this case, pure and doped pellets) seems feasible, as shown in a classification experiment.

II. Materials and Methods

Two different sets of pellets were used in the experiments, including both pure and doped UO_2 pellets from the UTGARD lab at Lancaster University [3-4]. Fig. 1 shows an image of the eight pellets analyzed, along with a table describing their composition, where the four pellets in the top of the image are pure pellets, while the four ones in the bottom are doped pellets.



Pellet Number	Code	Composition
1	U404-P3-3	UO_2
2	U404-P10-7	UO_2
3	U406-P8-2	Highly-Doped
4	U406-P7-2	Highly-Doped
5	U404-P10-10	UO_2
6	U404-P3-5	UO_2
7	U406-P8-1	Highly-Doped
8	U405-P7-3	Low-Doped

Fig. 1. Pellets used in the experiments: (a) RGB image of the eight pellets for reference, and (b) description of each pellet.

A hyperspectral image (and therefore, the spectral response) of these pellets was captured by the SWIR-640 system from Headwall Photonics Inc, which is a pushbroom scanning device operating in the SWIR range through 272 spectral channels. In order to avoid any potential contamination to the hyperspectral system, the nuclear pellets were placed inside a sealed box with glass top lid (see Fig. 2). This fused silica glass layer allows appropriate capture of hyperspectral data through it in the SWIR region, although small artefacts around the wavelengths 1400nm and 2250nm may appear.

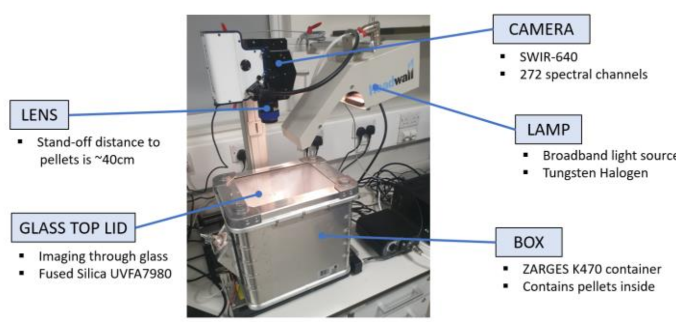


Fig. 2. Setup used for experiments, where a sealed box contains the pellets and the hyperspectral image is captured through a fused silica glass layer.

This summary was submitted for review on 4th May 2023. It is part of work funded United Kingdom's EPSRC under Grant EP/V051059/1.

J. Zabalza, P. Murray, and S. Marshall are with Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom, G1 1XW (e-mail: j.zabalza@strath.ac.uk).

A. J. Parker, M. Bandala, X. Ma, C. J. Taylor, and M. Joyce are with Department of Engineering, Lancaster University, Bailrigg, Lancashire, United Kingdom, LA1 4YR (e-mail: a.j.parker3@lancaster.ac.uk).

D. Hutchinson, P. Stirzaker, and D. Eaves are with Westinghouse Nuclear Fuel, Springfields, Preston, PR4 0XJ.

The classification (identification) technique applied to the captured hyperspectral image was the well-known Spectral Angle Mapper (SAM) [5], which measures the spectral similarity between the different pixels in the image and classifies them based on it. The SAM technique generated a pixel-wise classification map shown in Section III.

III. Results and Discussion

The spectral responses of both pure and doped pellets are shown in Fig. 3 and Fig. 4, respectively. These are the average responses from the 10x10-pixel areas as indicated in the figures.

The signatures found for all the pure pellets exhibit identical features (shape of the response), and the only difference is a small offset in intensity. This offset can be neglected as is due to the different spatial location of each pellet, resulting in a slightly different amount of light reflected from their surface. These responses show a number of features across the evaluated range, although peaks around 1400nm and 2250nm can be discarded as they are known to be artefacts from the fused silica glass layer through which the image was captured.

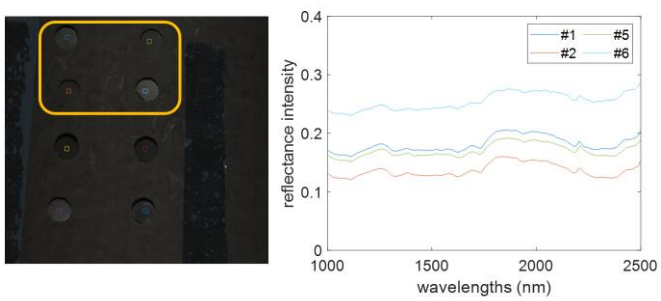


Fig. 3. Spectral responses of the four pure UO_2 pellets in the hyperspectral image: (a) composite image for reference, highlighting the region evaluated in each pellet, (b) responses (reflectance intensity) in the SWIR for each one of the four pellets. Significant features are revealed across the spectral range.

Unlike the pure pellets, the spectral responses found for the doped ones are much flatter and contain some different features, where the only difference between the four doped pellets is again the offset in reflectance intensity due to the different spatial location of each pellet. These two clearly distinctive types of responses (for pure and doped) are expected to allow the automated identification of these two groups of pellets.

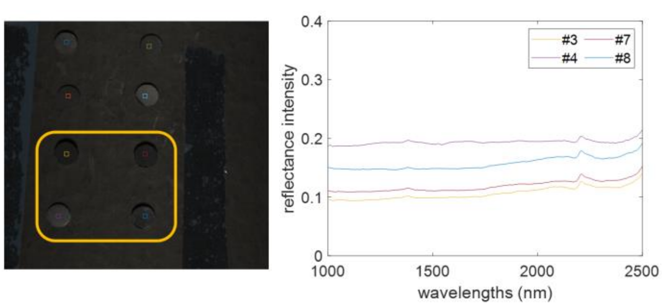


Fig. 4. Spectral responses of the four doped UO_2 pellets in the hyperspectral image: (a) composite image for reference, highlighting the region evaluated in each pellet, (b) responses (reflectance intensity) in the SWIR for each one of the four pellets. Features are different to those in the pure pellets.

The SAM technique [5] was used to perform a pixel-wise classification on the hyperspectral image. This technique was trained using reference spectra for four classes: (i) pure UO_2 pellets, (b) doped UO_2 pellets, (c) background, and (d) others. Fig. 5 shows the result of the classification, where the successful identification and detection of both types of pellets is evident, with the map capturing the four pure cases (green color) and the four doped cases (red color). There is a reduced percentage of pixels misclassified, mostly in the background, but this can be explained by several factors including individual pixel noise and the reduced amount of training in the SAM technique. More powerful classifiers, such as those based on machine and deep learning, would be expected to refine and further improve this classification map.

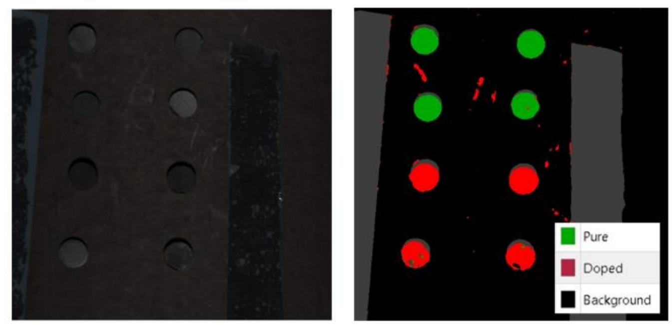


Fig. 5. Classification experiment based on the SAM technique: (a) composite image for reference, and (b) classification map where pixels in the image were classified into pure pellet (green color), doped pellet (red color), background (black color), and others (gray color).

IV. Conclusion

This work researched the potential use of HSI for the characterization and automated identification of nuclear fuel pellets with different compositions based on their spectral response in the SWIR region. Two clearly different responses were found for pure pellets and doped pellets, allowing their discrimination.

A classification map generated via the SAM technique showed good results and would demonstrate the HSI capabilities in this context. These preliminary results are promising and further work will be developed to validate the features revealed by the spectral responses. Complementary characterization and analysis based on surface properties or material microstructure will be explored.

References

[1] J. Zabalza, A.J. Parker, M. Bandala, P. Murray, S. Marshall, X. Ma, C.J. Taylor, M. Joyce, "Super resolution hyperspectral imaging based automated inspection of nuclear fuel pellets," in *IEEE Nuclear Science Symposium (NSS)*, Milan, Italy, 2022.

[2] A.J. Parker, J. Zabalza, M. Bandala, X. Ma, C.J. Taylor, P. Murray, S. Marshall, M. Joyce, "Passive, non-destructive enrichment measurement of sintered UO2 fuel pellets," in *IEEE Nuclear Science Symposium (NSS)*, Milan, Italy, 2022.

[3] R.J. Wilbraham, E.A. Howett, C. Boxall, D.I. Hambley, J.K. Higgins, "Simulated advanced gas-cooled reactor spent nuclear fuels: Determination of the O/U ratio - an XRD, XPS and Raman study," *Journal of Nuclear Materials*, no. 568, 2022.

[4] Z. Hieltz, "Processing and microstructural characterisation of UO2-based simulated spent nuclear fuel ceramics for the UK`s advanced gas-cooled reactors," PhD Thesis, Imperial College London, 2015.

[5] F. Kruse, A. Lefkoff, J. Boardman, K. Heidebrecht, A. Shapiro, P. Barloon, A. Goetz, "The spectral image processing system (SIPS) - interactive visualization and analysis of imaging spectrometer data," *Remote Sensing of Environment*, vol. 44, pp. 145-163, 1993.