SWIR Hyperspectral Detection of Uranium Dioxide in Simulated Fuel Debris using SAM and Machine Learning Methods

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Nuclear decommissioning following a severe reactor accident requires the retrieval of fuel debris, a mixture of melted fuel, cladding, structural steel and concrete. In this scenario, each retrieved object must be characterized to establish whether it contains fissile material before it is appropriately handled, cut or stored.

Many characterization methods currently in use are destructive, slow to analyse and require close contact with the material or even ex-situ analysis. Due to the highly radioactive nature of the debris, methods that can be carried out swiftly in-situ and be deployed at a distance (e.g. several metres from the objective) can significantly reduce the dose profile for retrieval teams and equipment. This work evaluates the use of short-wave infrared (SWIR) hyperspectral imaging (HSI) for rapid non-destructive fuel debris characterization, where the HSI images capture a reflectance spectrum at every pixel of a scene for locating uranium dioxide (UO_2) on the surface of simulated fuel debris.

In the experiments, three simulated fuel debris pellets containing sintered mixtures of UO_2, zirconium (Zr), and zirconium dioxide (ZrO_2) were imaged, together with pure UO_2, ZrO_2 and stainless steel as reference materials. Pixels in the fuel debris images were compared with the UO_2 reference using a spectral angle mapper (SAM). The resulting maps were validated against co-registered uranium maps obtained by scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM-EDS), which is highly accurate but not easily deployable in-situ. Additionally, a random forest classifier was trained on these SEM-EDS labels to classify each pixel in the spectral data as containing UO_2 or not, with one pellet used for training and the other two for testing.

Results show similar performance between the methods with an area under the receiver operating characteristic (ROC) curve (AUC) of 0.91 using SAM and 0.9 using the random forest, when tested on the latter 2 pellets. This demonstrates that for macro-scale analysis, SWIR imaging can detect UO_2 in similar locations to SEM-EDS, which is very useful given the more practical deployability of HSI. SAM uses only the UO_2 reference so is also tested on all 3 pellets and achieves an AUC of 0.87. A small correlation between the intensity of the UO_2 signature and the size of UO_2 regions is observed, which suggests a possible explanation for differences in performance between pellets. Preprocessing using quadratic detrending is shown to help target real UO_2 features with AUC measurements dropping significantly when this is not used.

This work shows that inspection techniques based on SWIR hyperspectral imaging can locate UO_2 on the surface of simulated fuel debris without contact, and potential classification methods can be automated for this purpose. Future work will focus on extending the analysis to more samples and different scenarios.