CLEAR CAM: Leveraging Physics-Informed GANs to Enhance Plutonium Detection Accuracy

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What is Continuous Air Monitoring (CAM)?

Continuous Air Monitoring (CAM) systems are critical safety devices used in facilities that handle radioactive materials. Their core function is to continuously sample ambient air and detect airborne radioactive particles, especially alpha-emitting isotopes like plutonium (Pu-239, Pu-238) and americium (Am-241). CAMs help identify any release of radioactive contaminants in real time, allowing swift response to minimize exposure.

1. PROTECTING HUMAN HEALTH

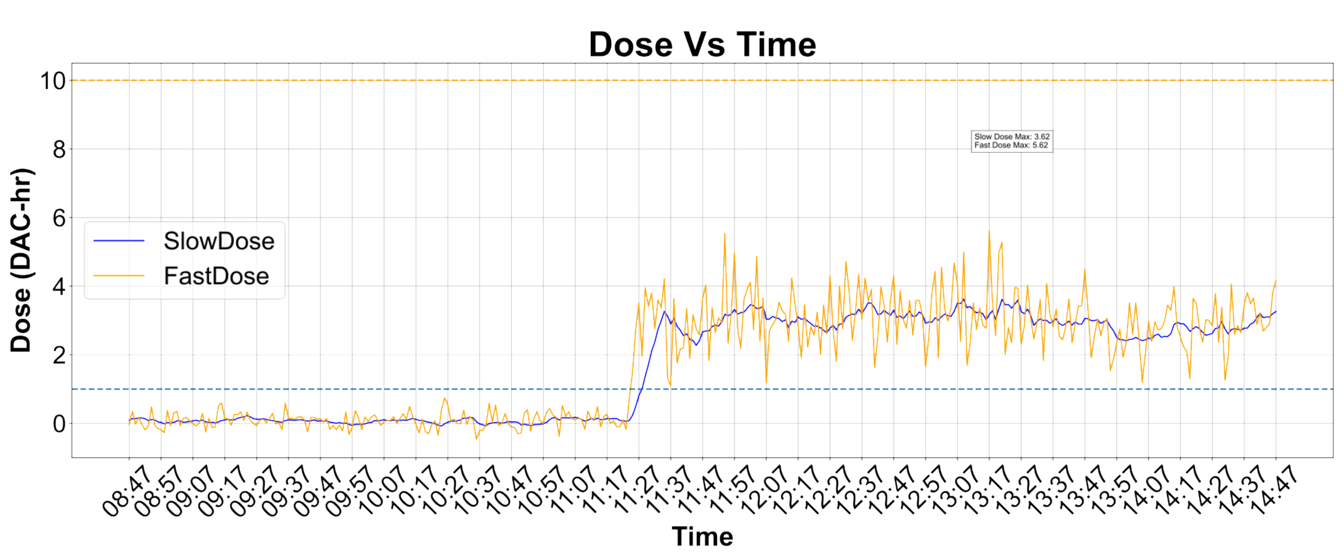
Alpha particles are extremely hazardous when inhaled. Even tiny quantities of airborne plutonium can cause significant internal damage due to the high ionization potential of alpha radiation. CAM systems are designed to be ultrasensitive, capable of detecting exposure levels well below 2 DAC-hours for Pu-239.

2. REAL-TIME INCIDENT DETECTION

A reliable CAM is a first line of defense against contamination events. These instruments continuously monitor the work environment and can trigger alarms within seconds if airborne activity exceeds safety thresholds. This gives staff time to evacuate, contain the problem, and begin decontamination.

3. REGULATORY COMPLIANCE

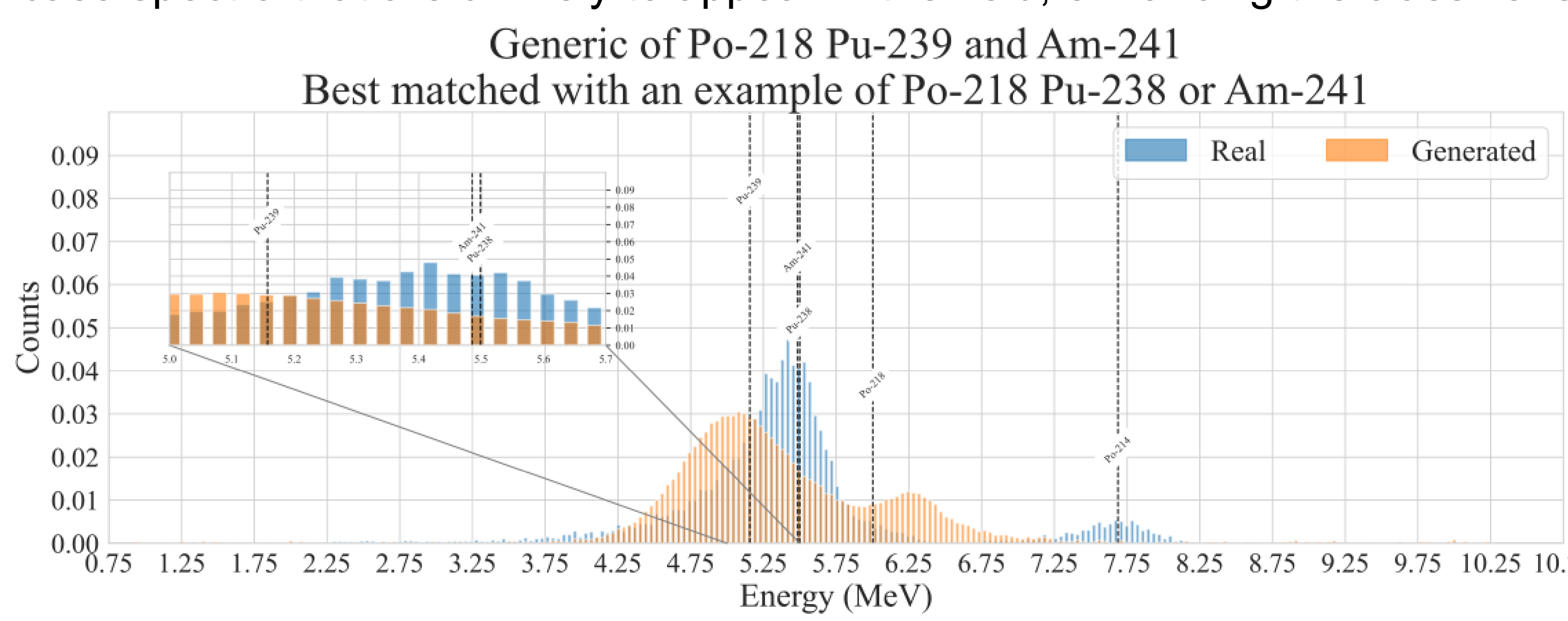
CAM systems generate time-stamped concentration and dose data, which is archived. This it ensures compliance with regulatory bodies like DOE, NRC, or IAEA, all of which require rigorous air quality monitoring in nuclear facilities.

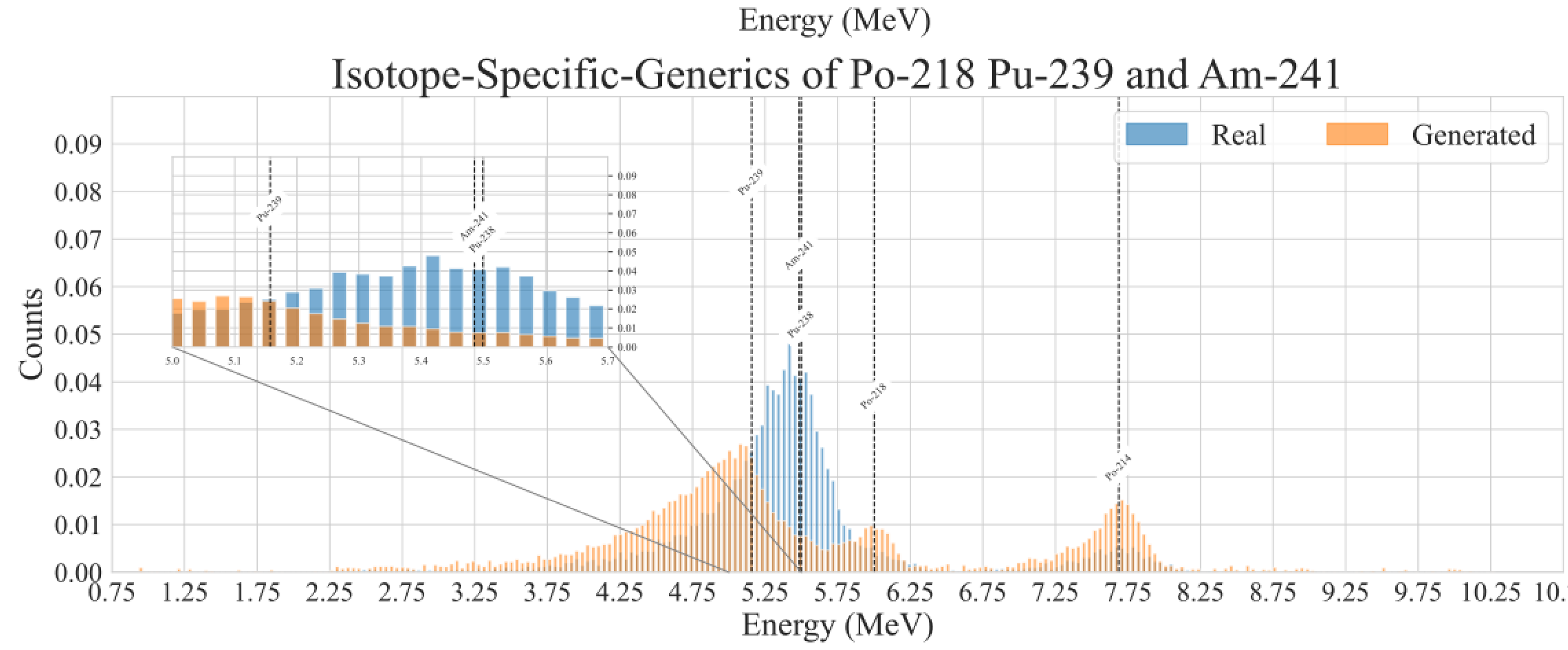


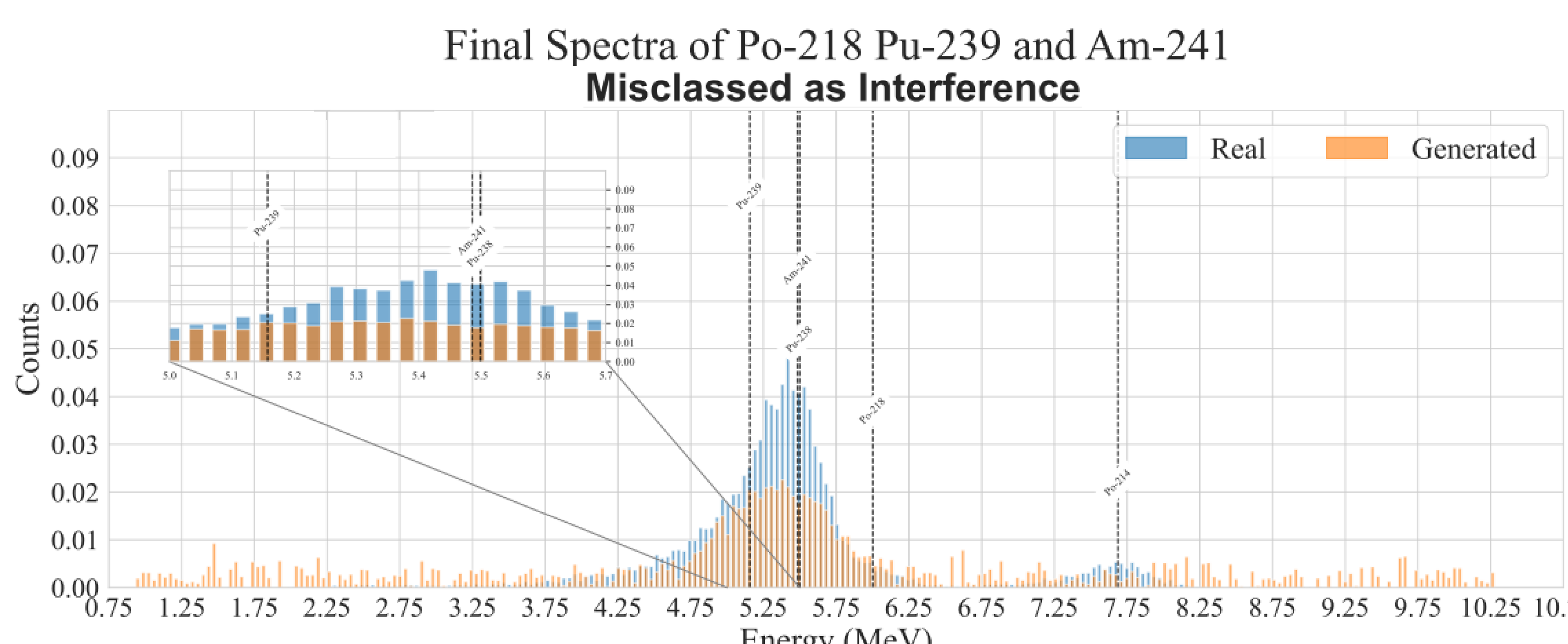
Problem: False Alarm Rate

TRADITIONAL CAM systems rely on peak shape analysis and spectrum deconvolution to distinguish between alpha-emitting isotopes with overlapping energies, such as Po-218 and Pu-239. However, these methods break down in high-background environments dominated by radon progeny, where the long spectral tails of radon isotopes significantly overlap with plutonium peaks. This overlap makes it difficult to reliably separate signals, leading to frequent false alarms and operational disruptions.

CLEAR CAM addresses the challenge of high false alarm rates by employing a generative adversarial network (GAN) framework. This framework consists of two neural network components: a classifier and a generator. The classifier analyzes input spectra to identify the isotopes present. In parallel, the generator produces synthetic spectra specifically designed to mislead the classifier into making incorrect identifications. Through this adversarial process, the classifier iteratively improves, learning to recognize subtle distinctions and establish more robust discriminative boundaries. In effect, the generator uncovers rare or edge-case spectra that are unlikely to appear in the field, enhancing the classifier's generalization and resilience.







1. CREATE GENERIC SPECTRA

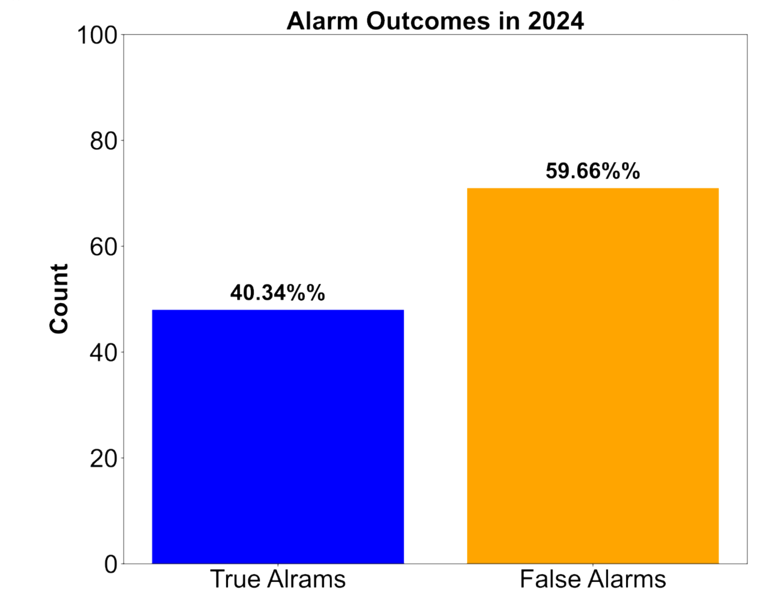
Create a generic set of spectra by placing slightly varying normal distributions with adjustable height, width, and center. These distributions are positioned at precise MeV values corresponding to the isotopes of interest. These are called _Generics._

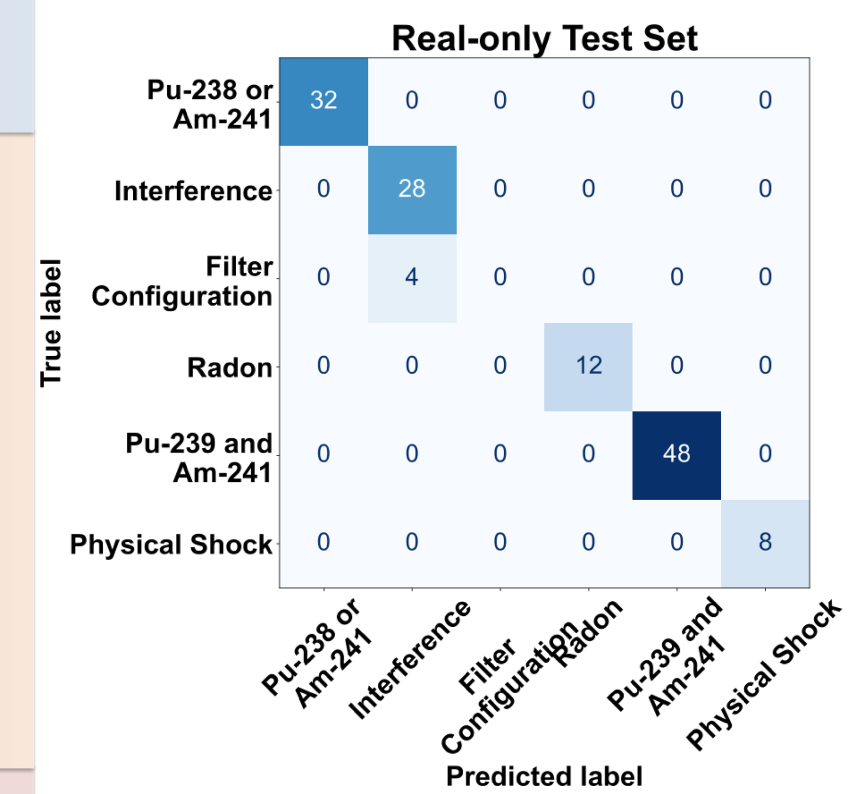
2. USE AI TO ADD ISOTOPE-SPECIFIC FEATURES

Next, take the generic spectra and pass it through a residual MLP model, this is our _generator_ model trained to add features observed in real-world field data. These features are based on the isotopes originally placed in the generic spectra. The output of this is called an _Isotope-Specific-Generics._

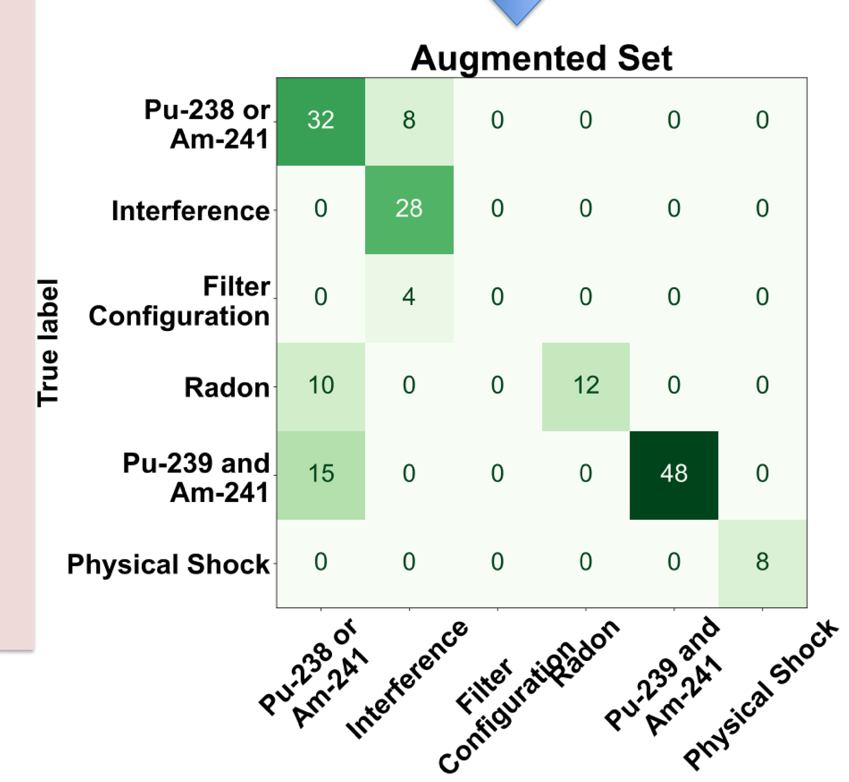
3. GENERATIVE ADVERSARIAL NETWORK (GAN) TRAINING

Fine-tune the Generator so that our Isotope-Specific-Generics fool classifier models, or the _adversarial_ models. The process is cyclic: Train classifier models on field data. Train the Generator to adjust and trick the classifier. Retrain classifier on synthetic spectra + field data. Retrain the Generator to fool the now improved classifier. Repeat until the Generator can only fool the classifier with unrealistic spectra.





After training we see weak spots exposed



TERMS

DAC (Derived Air Concentration): Airborne concentration of a specific radionuclide which, inhaled at a breathing rate (1.2 m³/hour) 2,000-hour work year, results in intake equal to one Annual Limit on Intake.

MeV (Mega electron Volt): A unit of energy used to identify isotopes by their particle emission energies

Fast Dose Window: Detects sudden releases. Averages two 60-second windows, checked every second.

Slow Dose Window: Tracks long-term exposure. Averages two 10-minute windows, checked every 5 seconds.

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