A SYSTEMATIC APPROACH TO HYPERSPECTRAL INTERPRETATION OF URANIUM MINES

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ABSTRACT
In addition to high-resolution panchromatic imagery, multispectral and hyperspectral imaging are now beginning to be used by safeguards regulators to help characterize nuclear-related materials. Advances in hyperspectral remote sensing have resulted in faster pre-processing times, better calibrated datasets, and improved mapping techniques. However, in the absence of reliable ground truth data and incomplete nuclear-based spectral libraries, mapping nuclear-related materials from hyperspectral imagery is still a challenge.

This paper proposes a systematic approach to mapping uranium mines and deposits from hyperspectral data in the absence of local ground data. The method is based on classical uranium deposition models and supporting materials obtained from large, known operating uranium mines and processing plants. The primary features of each model and mine are identified and tabulated, and a custom spectral library is then compiled for uranium ores, host rocks, rock assemblages, non-economic rocks and minerals, and alteration/weathering products. Secondary materials and by-products produced or needed by mines and mills are also included.

Using this concept, a preliminary hyperspectral examination of a uranium mine for one depositional model is presented. High-grade ore at Ranger Mine, Australia is differentiated from lower grades on the basis of their spectral signatures, and tracked to different locations on the mine site.

THE PROMISE OF HYPERSPECTRAL REMOTE SENSING
With photo-interpretation of high spatial resolution imagery, experienced analysts can identify and interpret *objects* through visual cues like shape, size, pattern, texture, shadow and association. Photo interpretation is of critical and central importance in the IAEA's examinations of Safeguards relevant buildings and other human construction. However it is very difficult if not impossible to accurately differentiate materials like aggregate, waste piles, mine tailings and ore stockpiles or type of processing plants using panchromatic imagery.

We are learning how to make chemical identification of *materials* at the front end of the fuel cycle using hyperspectral analysis. While uranium itself is present in deposits in very small concentrations, and is unlikely ever to be directly detected optically from space, the low concentrations require mining and processing of massive amounts of host and gangue materials (material of no economic value mined collaterally with the ore) that are difficult to hide. Even in underground mines, these waste materials are brought to the surface for processing and are stored in piles at the plant. Moreover, ores with high uranium contents are often diluted with waste materials before transport for safety reasons. All of these host and gangue materials are available for satellite interrogations along with other secondary materials and by-products.

CURRENT LIMITATIONS TO HYPERSPECTRAL SAFEGUARDS REMOTE SENSING

Hyperspectral remote sensing in mineral exploration is approaching maturity, but the application of the technology to Safeguards is relatively new. There are several current limitations:

1. In 2006 there is only one suitable source of open-source satellite hyperspectral imagery. The aging experimental HYPERION sensor on the American EO-1 satellite is several years past its design lifetime, has relatively low Signal to Noise, and is beginning to fail. Scheduling conflicts sometimes limit the possibility of acquiring data. This limitation will soon be resolved as many countries, including the US, Canada, Germany and Italy, are building or planning hyperspectral satellite sensors.
2. In 2006, it can be difficult to 'calibrate' hyperspectral imagery to ground-level Reflectance. That is, it is difficult to remove the affect of the atmosphere on the satellite spectral measurement. In order to identify a material from space, the space-based spectral signature must be matched with one measured in a lab or on the ground of known materials. Currently available atmospheric correction programs need improvement. We often need local spectral data from the ground in order to perform empirical calibrations. However atmospheric correction is the subject of much current research and we can expect that eventually Atmospheric Correction programs will improve.
3. In 2006, complete reference spectral libraries do not exist for safeguards applications. In order to identify a material by its spectral signature, one needs a comprehensive reference library that includes all relevant materials. This last limitation is the subject of the present paper.

A SYSTEMATIC APPROACH TO HYPERSPECTRAL INTERPRETATION OF URANIUM MINES AND PROCESSING PLANTS

With particular focus on the mines and processing facilities at the front end of the fuel cycle, we are taking a systematic approach to overcome the lack of a Safeguards-relevant spectral reference library. Using the IAEA (2000) defined uranium deposition models, we have begun by identifying the types of geologic environment of major uranium deposits compiled by the World Nuclear Association (2005) in Table 1.

Table 1. Depositional types of the highest producing uranium mines in 2004

Mine	Country	Main Owner	Mine Type	Geologic/Depositional Environment	Production (t U)	% of World Production
McArthur River	Canada	Cameco	Underground	Unconformity	7200	17.9
Ranger	Australia	ERA (Rio Tinto 68%)	Open Pit	Unconformity	4356	12.1
Olympic Dam	Australia	WMC	By-product/ Underground	Breccia Complex	3706	9.3
Rossing	Namibia	Rio Tinto (69%)	Open Pit	Intrusive	3038	7.5
McClean Lake	Canada	Cogema	Open Pit	Unconformity	2310	5.7
Rabbit Lake	Canada	Cameco	Underground	Unconformity	2087	5.2
Akouta	Niger	Cogema/Onarem	Underground	Sandstone	2005	5.0
Arlit	Niger	Cogema/Onarem	Open Pit	Sandstone	1277	3.2
Beverley	Australia	Heathgate	In-Situ Leaching	Sandstone	920	2.3
Vaal River	South Africa	Anglogold	By-product/ Underground	Quartz-Pebble Conglomerate	756	1.9
Top Ten Total					27,654	68.8

We then collated open source literature to help us understand the geology and other depositional features of each of the major deposit types (Figure 1), allowing us to begin to assemble tables of the types of mineralization in each category of deposit (Table 2).

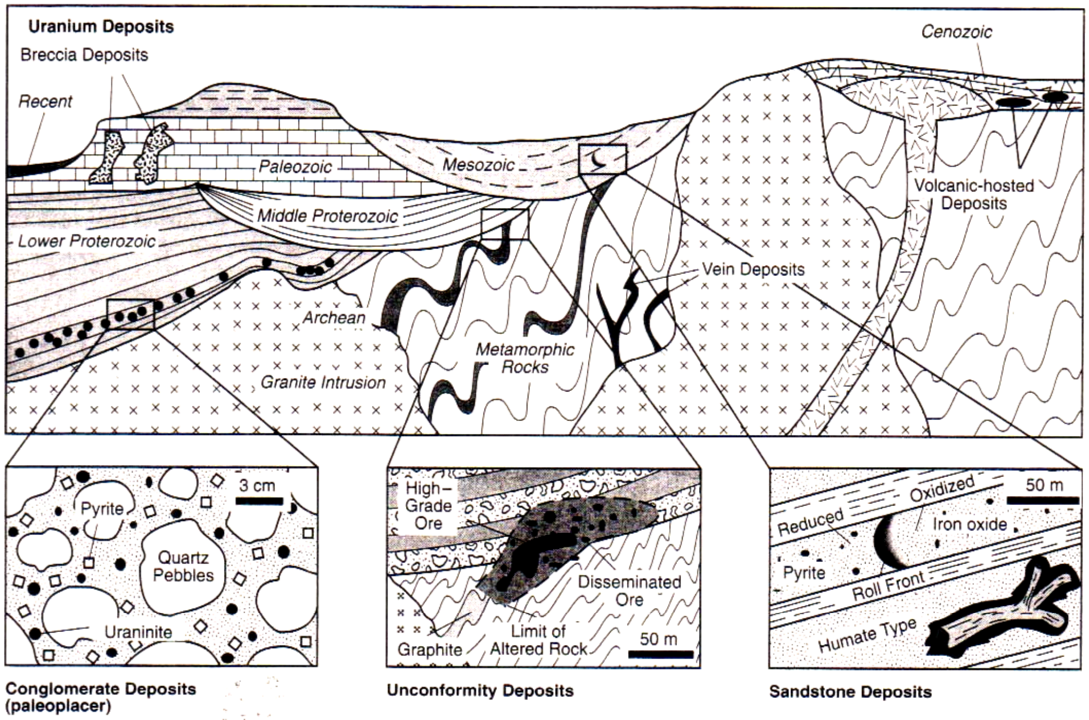


Figure 1. Geologic cross sectional settings of some important types of uranium deposits (Kesler, 1994). Not all types of deposits are shown in this figure.

This in turn allows us to begin to assemble a spectral signature library of the minerals and materials relevant to Safeguards, identify missing spectral signatures and acquire new ones.

Table 2. Important rocks and minerals associated with major uranium mines and deposits as categorized by IAEA (2000).

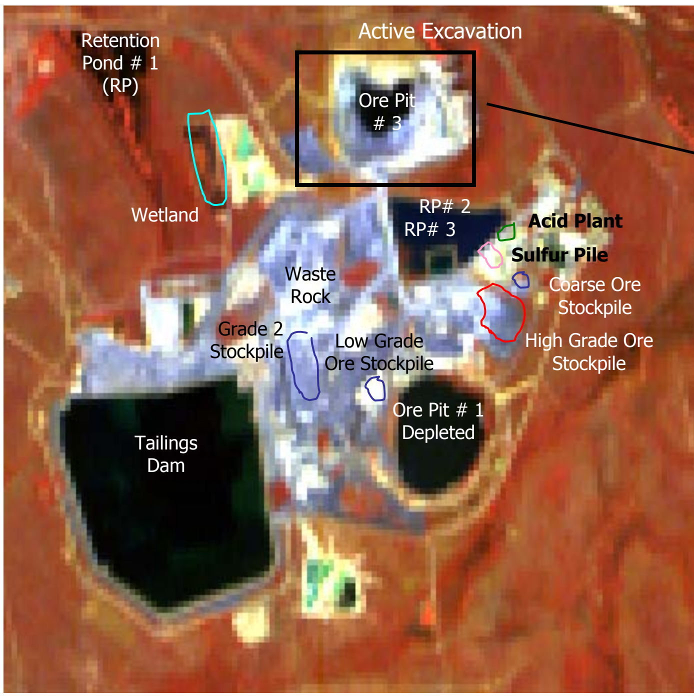
Deposit Type	Uranium Ore	Main Host/Associated Rock Types	Commonly Associated Gangue Minerals	Alteration Minerals	Major Mine or Type Locality
Unconformity Related	Uraninite, Pitchblende, Coffinite, Brannerite,	Amphibolite & Granulite facies, Metapelites, Calcsilicate, Metapsammites,-Arkosic Sandstone, Quartz Arenites, Schist, Gneiss	Calcite, Dolomite, Magnesite, Siderite, Chalcedonic Quartz, [1]Sericite, Illite, Chlorite, Dravite	Chlorite, Hematite, [1]Sericite, Illite, [2]Silica, Dolomite, Kaolinite, Dickite, Dravite	McArthur River, Canada McClean Lake, Canada Ranger, Australia
Sandstone	Uraninite, Pitchblende, Coffinite, Carnotite	Quartzose to Arkosic Sandstone, Feldspathic or Tuffaceous Sandstone, Sandstone-Mudstone Interface	Pyrite, Calcite	Hematite, Limonite, Calcite, Dolomite, Kaolinite	Beverley, Australia Akouta, & Arlit, Niger
Quartz-Pebble Conglomerate	Uraninite, Brannerite, Coffinite	Quartz-Pebble Conglomerate, Quartzose Arenites	*Not Available*	Chlorite, Muscovite, Pyrite *Matrix*	Pronto, Canada Vaal River, South Africa

Deposit Type	Uranium Ore	Main Host/Associated Rock Types	Commonly Associated Gangue Minerals	Alteration Minerals	Major Mine or Type Locality
Vein	Uraninite, Pitchblende, Coffinite, Brannerite	Granite, Syenite, Felsic Volcanic	Calcite, Dolomite, Chalcedony, Hematite, Feldspars	Chlorite, Hematite, Episyenite, Feldspars	Beaverlodge, (Sask.) Canada
Breccia Complex	Uraninite, Coffinite	Granite or Hematite Breccias and other fragmented sedimentary, volcanic, and intrusive	Sericite, Carbonates, Chlorite, Quartz, Fluorite, Barite	Sericite, Hematite, Chlorite, K-Feldspars (Microcline, Sanidine, Orthoclase)	Olympic Dam, Australia
Intrusive	Uraninite, Davidite	Alaskite, Granite, Monzonite, Syenite, Carbonatite, Syenitic Pegmatite	*Not Available*	Hematite	Rossing, Namibia; Phalaborwa, South Africa
Phosphorite	Fluorapatite, Apatite	Phosphate Pellets in Limestone, Dolomite, Clay, Siliciclastic Sediments	Limestone, Dolomite, Gypsum, Chert	*Not Available*	Central Florida, USA; Akashat, Iran
Collapsed Breccia Pipe	Uraninite, Pitchblende, Coffinite, Montroseite	Quartzose to Arkosic Sandstone, Conglomerate, Breccia, Limestone	Pyrite, Marcasite, Calcite, Dolomite, Barite, Anhydrite, Siderite	Carbonates, Calcite, Dolomite, Kaolinite	Orphan Lode, USA; Easy 1, USA
Volcanic	Uraninite, Coffinite, Carnotite, Uranophane	Andesite, Rhyolite, Granite, Monzonite, Carbonaceous Tuffaceous Mudstone, Rhyolitic Ignimbrite	Fluorite, Quartz, Carbonates	Silica, Kaolinite, Montmorillonite, Alunite	McDermitt, USA Marysvale, USA
Surficial	Carnotite	Calcrete (conglomerate mixture of sand & gravel cemented by calcium carbonate)	*Not Available*	*Not Available*	Yeelirrie, Australia
Metasomatite	Uraninite, Thorite, Uranothorite, Brannerite	Albite, Aegirinites, Alkali Amphibole	Calcite, Dolomite	Hematite, Magnetite, Carbonates	Espinharas, Brazil
Metamorphic	Uraninite, Pitchblende	Metasediments, Skarn	Silica, Pyrite, Galena, Hornblende, Prehnite, Calcite	*Not Available*	Mary Kathleen, Australia; Forstau, Australia
Lignite	*Not Available*	Lignite, Clay, or Sandstone	*Not Available*	*Not Available*	Dakota, USA
Black Shale	*Not Available*	Carbonaceous Marine Shale	*Not Available*	*Not Available*	Alum Shale, Sweden
Others					
Limestone	*Not Available*	Limestone	*Not Available*	*Not Available*	Todilto Limestone, USA
Salt Domes	Pitchblende	Rhyolite, Rhyolitic Tuff?	*Not Available*	*Not Available*	Gachin, Iran

Our library is still far from complete, but it is a beginning. Some of the listed rocks and minerals are still too generic and represent only some of the major deposit types. With time, we will fill in more missing minerals and corresponding signatures and add other relevant materials like by-products, feed-stocks and building materials used in various parts of the world. This is a large effort and will require the assistance and collaboration from our colleagues. We call on the IAEA and other Safeguards Support Programs to join us in this attempt to make hyperspectral remote sensing more useful to Safeguards.

A HYPERSPECTRAL CASE STUDY OF AN OPEN PIT *UNCONFORMITY-TYPE* URANIUM MINE

Ranger Mine in Australia is a large open pit mine, classified as an *unconformity type* uranium deposit. Figure 2 shows a Hyperion image of the site and lists some of the natural and secondary minerals and other materials that, based on the geology, might be expected from this type of uranium deposit and mining operation. Some specific features (active ore pit, stockpiles, waste rock, etc) have been tentatively identified based on our image analysis or direct ground truth from several sources (Leslie *et al*., 2002; McKay *et al*., 2001).



ORE PIT # 3
(Active Excavation)

Ore: Uraninite, Brannerite, Pitchblende, Thucholite

- **High Grade Ore** [~8% U_3O_8]: Ore +/- Schist +/- Chert
- **Normal Grade Ore** [~0.19 to 0.29% U_3O_8]: Ore +/- Schist +/- Pegmatite +/- Carbonate

Host Rock [Also in Tailings?]: Chlorite Schist, Microgneiss, Carbonate

Gangue [Also in Tailings?]: Chlorite, Quartz, TiO_2, Hematite, Apatite, Pyrite, Chalcopyrite and Galena

Alteration Minerals [Extending over 1 km from ore deposits]: Sericite - Chlorite +/- Kaolinite +/- Hematite

Figure 2. Hyperion hyperspectral image showing minerals and related materials that might be expected in an *unconformity-type* open pit uranium mine.

The image was empirically calibrated and several Regions of Interest (ROIs) were delineated. The mean spectra for the different ROIs were evaluated using the ENVI™ Spectral Analyst. Side-by-side comparisons of the ROI mean spectra and matches from the USGS spectral library are shown in Figure 3. The top Spectral Analyst matches were sorted and only the ones considered to best represent the area are shown.

It should be noted that the matching library spectra shown in Figure 3 are not necessarily the best top matches selected by the Spectral Analyst. The USGS spectral library was assembled for other kinds of environments and applications, and while it contains spectra representing hundreds of materials, most of them are not found, or will never occur in uranium deposits or mines. This is one of the main difficulties when attempting to identify image-based spectra from existing generic spectral libraries. *The analyst must select from the options presented, those spectra that are relevant to the study area. In order to do this, some knowledge of the geology of the site is required.* Our method and Safeguards library is an attempt to partially alleviate this problem.

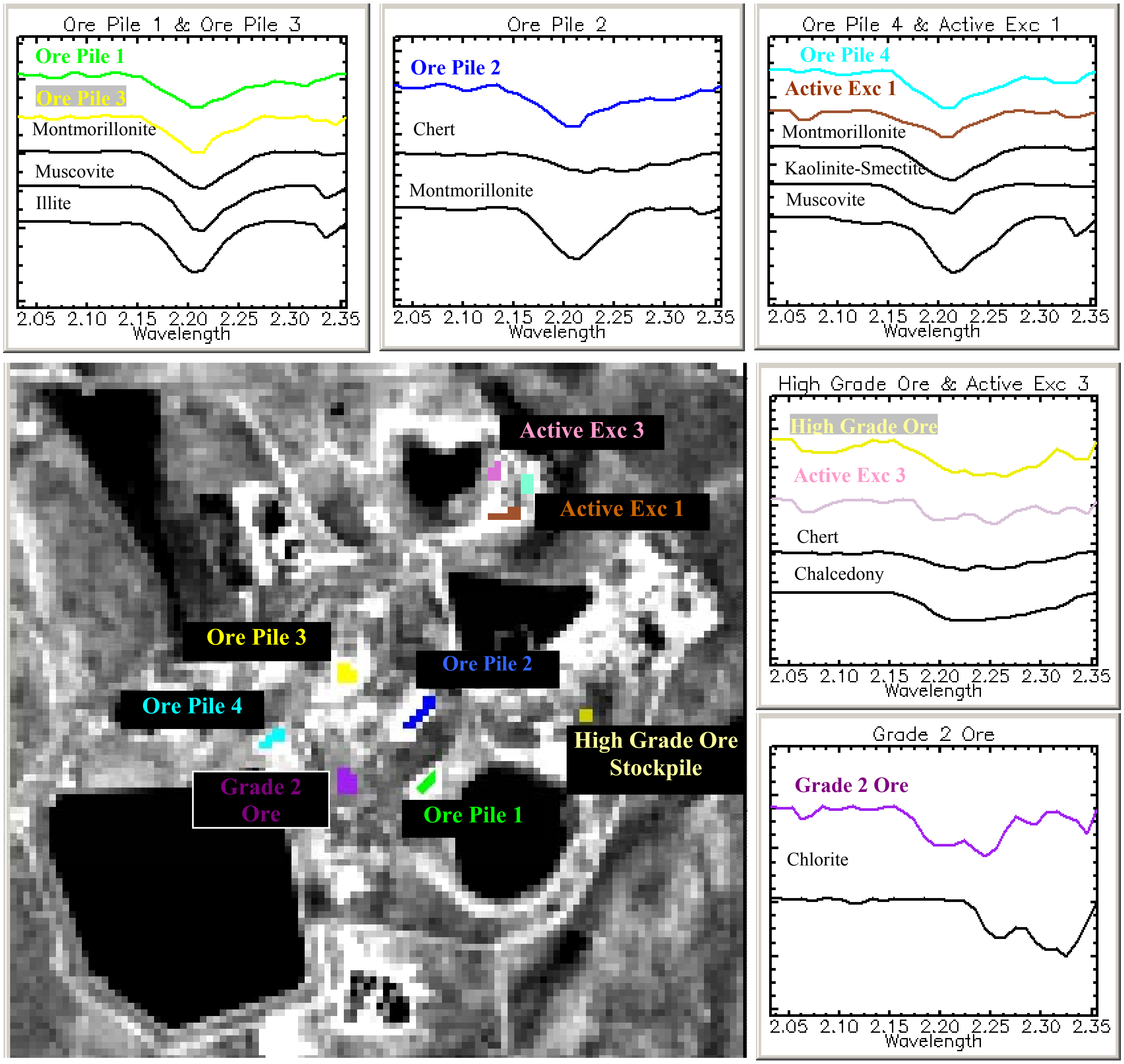


Figure 3. Single band Hyperion image showing delineated ROIs and matched spectra results evaluated from the USGS Spectral Library. For simplicity, similar spectra are grouped together and not all ROIs are shown. All spectra are stacked and Continuum Removed.

In spite of the limitations, the mean image spectra of the ROIs matched relevant library spectra and the minerals so identified appear to be well correlated with compiled ground studies. Open source literature (McKay *et al*., 2001) reports that the high-grade uranium ores are being mined between the chert and chloritised schist layer. In fact, in our hyperspectral analysis, chert appears high on the list in the high-grade ore stockpile, at ore pile 2, and in the active area at 'Active Exc 3'. Further, we can differentiate the ore types *within* the active excavation. We see that the ore exposed at the south end of the active excavation, at 'Active Exc 1' is spectrally very different from the high-grade ore. It has a single deep absorption feature around 2.2 microns, and is spectrally similar to montmorillonite. It is apparently being deposited on ore pile 4.

The low-grade and waste piles (ore piles 1, 2 and 3) are similar but not identical to ore pile 4. The other identified minerals with high scores in the Spectral Analyst are the minerals montmorillonite, muscovite, chlorite, kaolinite-smectite, and illite. Except for montmorillonite, all of these minerals are listed as alteration minerals or rock minerals reported to occur in the area. The spectra of montmorillonite, kaolinite-smectite, and muscovite are so much alike in the shortwave infra-red that they can be easily confused. It should also be noted here that some of these image-based spectra were extracted from ore stockpiles that have been sorted according to grade, and cannot necessarily be considered pure. In the past, montmorillonites have sometimes been called ‘smectites’.

When compared to the USGS spectral library, the most logical spectral match for the Grade 2 ore stockpile ROI is chlorite, but the spectral shapes are poorly matched. Low-grade uranium ores are reportedly mined in the schist, microgneiss, or carbonates (McKay *et al*., 2001), and in rocks that are severely brecciated (broken up) and extensively invaded by chlorite veins in the ore zone. The poor match between the Grade 2 ore and this library probably indicates mixed spectra arising from mixed materials.

DISCUSSION

Applied indiscriminately, the use of generic spectral libraries to identify image-derived spectra can give high matching scores that can be misleading, and lead the naïve analyst to ‘find’ materials that could never occur in the area under examination. A specialized Safeguards spectral library with entries for relevant minerals and processing-related materials will help filter out these false positives by making it possible to match image spectra against a *relevant* library spectra. Alternatively, the analyst will be able to use Safeguards spectral library entries as “spectral endmembers” to search for selected materials in the image and produce a more plausible mineralogical map of the site.

Compilation of a single spectral library geared to Safeguards monitoring is no easy task. The library must be in a format that is universally acceptable, user friendly, and easily accessible. Methods of acquisition of the reference spectra must be standardized and well-reported, and international collaboration and training will be required.

Finally, uranium deposits can occur in diverse geologic conditions and environments. As more uranium deposits are found and better understood, the current IAEA (2001) uranium deposition model will eventually expand and evolve. As with any lasting robust system, our methods and the safeguards spectral library will have to keep abreast of these changes.

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