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Field Demonstration of a Portable, X-Ray, K-Edge Heavy-Metal Detector

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Abstract

Under the Characterization, Monitoring, and Sensor Technology Crosscutting Program, we have designed and built a K-edge heavy-metal detector that measures the level of heavy-metal contamination inside closed containers in a nondestructive, non-invasive way. The device employs a volumetric technique that takes advantage of the X-ray absorption characteristics of heavy elements, and is most suitable for characterization of contamination inside pipes, processing equipment, closed containers, and soil samples. The K-edge detector is a fast, efficient, and cost-effective in situ characterization tool. More importantly, this device will enhance personnel safety while characterizing radioactive and toxic waste.

The prototype K-edge system was operated at the Materials and Chemistry Laboratory User Facility at the Oak Ridge K-25 Site during February 1997. Uranium contaminated pipes and valves from a UF_6 feed facility were inspected using the K-edge technique as well as a baseline nondestructive assay method. Operation of the K-edge detector was demonstrated for uranium contamination ranging from 10 mg/cm^2 to 6000 mg/cm^2 and results from the K-edge measurements were found to agree very well with nondestructive assay measurements.

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1. Introduction

Within the DOE complex there are large quantities of radioactive and hazardous chemical waste that exist in a broad variety of forms, toxicity, and storage conditions. There are 3700 contaminated sites, with 500 facilities now surplus, and as many as 7000 expected to be declared surplus in the coming decades[1]. Most of these facilities will require cleanup of hazardous wastes before decommissioning. Efficient, safe, cost-effective methods of characterizing these waste materials are needed to assist in the timely cleanup of these sites. Due to the hazardous nature of the contaminants, a nondestructive non-invasive technique is preferred for characterization and for monitoring the decontamination processes.

Heavy-metal contaminants, including radioactive metals such as uranium and plutonium, are present in many of the weapons production facilities. Significant deposits often remain in processing equipment after it has been shut down. As this equipment is often massive and of a complex geometry, it is generally difficult with existing technologies to characterize deposits and verify that equipment can be safely disposed of or recycled.

Many very accurate chemical and optical characterization techniques are available provided that one has access to the sample. However because of the hazardous nature of radioactive and mixed toxic waste, a nondestructive non-invasive technique that minimizes the disturbance of the contaminant and avoids the exposure of personnel to hazardous material is strongly desired. Currently used nondestructive assay (NDA) technologies are limited to use for radioactive contaminants, and typically have a measurement uncertainty of 50% or more depending on the geometry of the material being inspected.

K-edge densitometry is a technique that offers promise in addressing these problems. In previous work[2-4] we have evaluated and enhanced this method to identify and quantify the presence of heavy elements in a mixture. The technique is non-invasive, nondestructive, and most suitable for characterization of heavy metals present inside closed containers.

In this report we present a brief description of the K-edge technique, and describe the prototype mobile instrument which we have constructed. This is followed by a summary of results from a field demonstration of the prototype device carried out at the Oak Ridge K-25 Site. We conclude with an analysis of the range of applicability of K-edge densitometry.

2. The K-edge Technique

K-absorption-edge densitometers have been used to measure and monitor the amount of uranium and plutonium in samples from several facilities around the world. These facilities include Los Alamos National Laboratory, Oak Ridge Y-12 Plant, Savannah River Plant, International Atomic Energy Agency (IAEA) Safeguards Analytical Laboratory, and La Hague, France reprocessing plant[5]. These applications were part of the safeguard programs at these facilities and the densitometers were optimized to measure several tens of grams per liter of uranium and/or plutonium in solution. The uranium and plutonium solutions were placed in standard containers where the geometry was controlled very precisely, thus allowing an accuracy better than 1% in these measurements[6]. For in-situ measurements associated with decontamination and decommissioning applications, the matrix material is often not known or

has a very complex composition and geometry. Nevertheless, we have demonstrated that under such conditions an accuracy of 10% is achievable using the K-edge technique[2-4]. This compares very favorably with uncertainties of 50-100% typically quoted for NDA techniques [7].

The absorption of photons is governed by the binding energies of atomic electrons. Each element has a unique distribution of its atomic electrons, with the K-shell having the highest binding energy. When a photon has just enough energy to liberate one of the atomic electrons there will be a sudden increase in the rate of absorption. This is indicated in Fig. 1 where the attenuation coefficients for gold and uranium are plotted as a function of X-ray energy. The K-edge for gold is at 80.7 keV, while the K-edge for uranium is at 115.6 keV, corresponding to the binding energies for the K-shell electrons in these atoms.

Figure 1. X-ray absorption coefficients for gold and uranium.

The basic setup for making a K-edge measurement is diagrammed in Fig. 2. A X-ray beam is made to pass through a sample to a collimated energy-sensitive X-ray detector. A typical X-ray spectrum generated by a tube using a tungsten target is shown in Fig. 3. Material placed in the beam will preferentially absorb low energy X-rays. At an energy corresponding to an absorption edge for an element, there will be a sudden change in the transmission rate, resulting in a step in the transmitted X-ray spectrum as indicated in Fig. 4 for a gold sample placed in the beam.

Figure 2. Basic setup for making a K-edge measurement.

Figure 3. Bremsstrahlung spectrum from X-ray tube operated at 100 kV.

Figure 4. X-ray transmission spectrum through a gold foil.

The abrupt change in the transmitted intensity at the K-edge energy identifies the type of contaminant. The amount of contaminant present can be calculated based on the size of the edge.

As indicated in Fig. 5, approaching the absorption edge from the left, the transmitted X-ray intensity is given by

$$I(E_-) = I_0(E_-)e^{-\mu(E_-)X}, \quad (1)$$

where, $I_0(E_-)$, and $I(E_-)$ are the incident, and transmitted photon flux, respectively, at an energy very close to the edge from the left, $\mu(E_-)$ is the linear attenuation coefficient of the sample material at that energy, and X is the thickness of the sample. Similarly when we approach the edge from the right,

$$I(E_+) = I_0(E_+)e^{-\mu(E_+)X}. \quad (2)$$

Figure 5. X-ray transmission spectrum in the vicinity of the K-edge of an element.

Assuming that we are extremely close to the edge, such that $I_0(E_+) = I_0(E_-)$, we can combine Eqs. 1 and 2 to solve for the thickness,

$$X = \frac{\ln \left[\frac{I(E_-)}{I(E_+)} \right]}{\mu(E_+) - \mu(E_-)}. \quad (3)$$

Notice that the incident X-ray flux is not a factor in the thickness calculation. It is for this reason that the K-edge technique is not sensitive to the type or shape of matrix materials in the sample. To first order the accuracy will be determined by the statistics of the intensity measurements.

In practice, because X-ray detectors have finite energy resolution, we cannot obtain the intensities, $I(E_+)$ and $I(E_-)$, directly from the spectrum[8]. Instead we define two windows above and below the K-edge and use a least squares fitting curve to extrapolate the data points to the K-edge itself. The windows must be chosen far enough away from the edge that the detector resolution will not have an effect on the extrapolation. One must be careful to avoid fluorescence

peaks and edges from other elements that might be present. It is also important that background radiation not contribute to the spectrum in the vicinity of the K-edge. This could come from scattered X-rays that have not passed through the contaminant or from natural radiation emitted by radioactive contaminants. To obtain the best accuracy with the K-edge technique, corrections for these effects must be made as well as for slight biases that can be introduced to the spectrum due to electronic pileup or absorption in the matrix material. By applying these corrections, in theory it is possible to obtain results with an accuracy of better than 1% [5,6]. As our goal is to make measurements with 10% accuracy, it will generally not be necessary to make these corrections.

3. Prototype Mobile K-Edge Inspection System

To demonstrate the applicability of this technique to in situ measurements, we have assembled a prototype system consisting of four major components: a X-ray generator, a monochromator assembly, a detection system consisting of the X-ray detector and an imaging system, and a data acquisition system consisting of an industrial personal computer running a Windows-based user interface software to control the device. Figure 6 shows a schematic drawing of the prototype K-edge system, and Figs. 7 and 8 are photographs of some of the system components.

Figure 6. Schematic drawing of the prototype K-edge heavy metal detector.

The X-ray generator is a Philips constant potential industrial X-ray system (model MG325 with MCN323 tube head and MGC40 controller). The X-ray tube has a maximum voltage of 320 kV and a maximum tube load of 4.2 kW. The tube head is mounted on a support frame linked to the detection system, and is connected by 32 foot cables to the high voltage supply and the cooling pump (for greater flexibility, a set of cables twice as long is also available). The support frame can be easily dismantled and reassembled to suit the configuration of the inspected object. The high voltage supply and the cooling pump are carried on a cart

Figure 7. Views of the detector system (left) and the X-ray source (right). The detector system consists of a Ge detector (to the left in image) shielded by a tungsten box with an adjustable collimation, and a real-time X-ray imager (black box to right in image). The X-ray source is a collimated 320 kV industrial X-ray tube. X-rays are emitted in a narrow cone beam from the hole at the center of the image. The monochromator is to the left in this image. For operation it is centered on the beam. The pipe seen in the image to the left is six inches diameter with $\frac{1}{2}$ inch thick wall.

Figure 8. K-edge system control panel showing X-ray generator control (bottom) and PC monitor used for system setup and display of results.

enclosed with an aluminum box with HEPA filters for protection from contamination by radioactive materials. The X-ray tube, detectors, and cables can be wrapped in plastic to protect them from contamination.

The detection system consists of an energy-sensitive X-ray detector and a real-time X-ray imaging system (see Fig. 7). The X-ray detector is an EG&G ORTEC high purity germanium detector (HPGe model GLP-16HCR-S) with a crystal 16 mm in diameter and 13 mm thick. The HPGe detector was chosen based on its excellent energy resolution which is important for obtaining accurate and high-sensitivity K-edge measurements[8]. The detector is cooled using a 1.2 liter liquid nitrogen dewar that can be operated in any orientation. The detector is connected to a model 672 EG&G ORTEC amplifier, and to an EG&G ORTEC TRUMP Multichannel Analyzer (MCA).

The imaging system can be used as an aid in aligning a sample with respect to the X-ray source and detector. The system consists of a gadolinium (Gd_2O_2S) phosphor screen and an intensified CCD video camera (Photon Technology International model IC-100), connected to a Data Translation model DT3155 frame grabber computer board. The HPGe detector and imaging system set next to each other on a platform that can be moved to center one system or the other on the X-ray beam. Because heavy metals are strong X-ray absorbers, they will generally produce good contrast in X-ray images. The real-time X-ray image provides a quick qualitative indication of heavy metal location. The HPGe detector can then be positioned to obtain a precise measure of contamination.

To detect very low concentrations ($< 10 \text{ mg/cm}^2$) of a contaminant requires high statistics at the K-edge energy. This can be achieved by operating the X-ray tube at high current and high voltage. However, this will generally lead to a situation where high-energy X-rays will dominate the spectrum and saturate the detector electronics. To get around this limitation we have implemented a X-ray monochromator in the system.

The monochromator selects a narrow band of X-ray energies around the K-edge of interest. The monochromator will then allow the photons in this energy band to pass through to the inspected object and then to the detector, while the rest of the incident X-ray beam is blocked by a thick tungsten plate. The energy of the diffracted beam can be controlled by varying the angle between the incident beam and the diffraction crystal according to Bragg's law,

$$2d \sin\theta = n\lambda \quad n = 1, 2, 3, \dots \quad (4)$$

where d is the spacing between two successive planes in the crystal (for graphite $d = 3.354$ angstrom), λ is the wavelength of the diffracted X-rays, and θ is the angle between the incident rays and the plane of diffraction (for a more thorough description of the physical principles and a schematic of the structure of the monochromator see Reference 2). The monochromator can be used to select energy bands ranging from 25 to 125 keV. This wide range of energies makes the device suitable to detect contaminants ranging from cadmium to plutonium.

Very precise and accurate control over the angle θ is necessary to select the required energy and to ensure a maximum diffracted photon intensity. To achieve this precision we have used computer controlled stepping motors in construction of the monochromator. The motors are controlled via an RS-232C Serial Interface. The monochromator assembly sets on a translation

stage so that the whole assembly can be moved to allow for open collimation imaging of the object of interest. The diffraction crystal is a highly oriented pyrolytic graphite crystal with a mosaic spread of 0.4 degrees (grade ZYA) to diffract X-rays.

Operation of the K-edge system is controlled through a PC located in the system control rack (Fig. 8). This rack can be positioned 50-100 feet from the X-ray tube, minimizing the risk of X-ray exposure for the operator. The driving software is a Microsoft Windows based program. The main menu is shown in Fig. 9.

Figure 9. The main menu in the K-edge detector driving software.

The imaging capability is used as a quick scan for large deposits of heavy metals and as an aid in aligning the system with respect to the sample. The software controls the CCD camera through interaction with the frame grabber board (DT 3155). As shown in Fig. 10, the user can continuously acquire images at a rate of 30 frames per second, or average or integrate a number of frames for improved image quality. Images can be saved to a disk file and recalled for later reference. The software also allows the user to look at the intensity distribution along a vertical or horizontal line (slice) in the image.

Figure 10. The Windows interface used for acquiring real-time X-ray images.

The "Alignment" button opens up a window (Fig. 11) that is used for the initial alignment of the diffracted beam and the X-ray detector. Options for calibration of the energy and position scales are available. It should be necessary to use these only if components in the system are changed. Under normal operation, after power up, the user would press the "Home" button to initialize the system for making measurements. The device has been calibrated for the inspection of several common contaminants, such that the operator needs only to choose from a

list of contaminants and the device will automatically be initialized for operation. The visual display gives the user an indication of the direction of motion of the different components in the system.

Figure 11. The window used for initial alignment of the K-edge detector.

Once the initial alignment is accomplished, the system is ready for conducting the K-edge measurement. Pressing "Acquire" opens up the window shown in Fig. 12, which communicates with the MCA card and collects the X-ray spectrum. The operator can use the button "Calculate" to get a measurement of the amount of contaminant present in the inspected object. The output is displayed in units of mg/cm^2 and microns of equivalent thickness (metallic density) of the contaminant. Once the accuracy of the measurement reaches the desired level, the user can then save the file and move on to a new measurement.

Figure 12. The K-edge detector data acquisition window.

4. Field Demonstration

To demonstrate the viability of making in-situ measurements, we transported the prototype K-edge system to the Oak Ridge K-25 Site for a series of demonstrations during the period from the 29th of January through the 7th of February, 1997. The demonstrations took place in the K-1006 building at the Materials and Chemistry Laboratory (MCL) User Facility. We were able to set our equipment up and have it ready to operate within 24 hours of arrival at Oak Ridge.

To check the accuracy of the K-edge detector after it was set up at the MCL we have measured the amount of uranium present in a calibration sample of known thickness. The sample was a 2 cm diameter foil weighing 0.3 gram made of metallic uranium, corresponding to a concentration of $96 \pm 10 \text{ mg/cm}^2$. The calibration sample was placed inside a 0.25 inch wall steel pipe and the real-time radiographic image shown in Fig. 13 was acquired. (Note that due to reproduction limitations, printed images in this report will not show the same contrast that is available on a display screen.) The uranium foil can be clearly seen at the center of the image. After verifying the location of the foil, we positioned the HPGe detector to acquire K-edge data. Five measurements, each lasting 90 seconds, were made with X-ray generator settings of 180 kV and 9 mA. All gave consistent results, and the average measured concentration of uranium was $89 \pm 5 \text{ mg/cm}^2$, which compares very well with the known amount. Figure 14 shows the X-ray spectrum from one of these measurements.

Figure 13. X-ray image of a 2 cm diameter uranium foil placed inside a 0.25 inch wall steel pipe.

Figure 14. K-edge absorption spectrum for a 96 mg/cm² uranium foil.

Samples of 1 inch inside diameter and 1/8th inch wall thickness pipes which were cut out of a UF₆ feed facility, were brought to the MCL. (It is believed that the pipes are monel, but that has no bearing on the success of the K-edge measurement.) Contamination levels in the pipes ranged from barely detectable to nearly full, so they provided a good range for testing the equipment. The deposits appear to be oxide and fluoride compounds of uranium. Photographs of representative pipes are shown in Fig. 15. The samples were contained in mylar bags to avoid contamination of the equipment. For in-situ measurements, the K-edge equipment would be bagged in plastic instead of the samples. Figure 16 shows one of the pipes positioned in the K-edge system for inspection.

In general it will not be feasible to make detailed K-edge measurements covering the entire volume of a sample. A reasonable strategy is to use the real-time image to determine the (non) uniformity of any deposits, and then make K-edge measurements at selected points and interpolate between these measurements to obtain a value for the total amount of contaminant.

The pipes we inspected ranged in length from 2-5 feet. We have acquired real-time X-ray images and made K-edge measurements at intervals of 4-8 inches for two perpendicular orientations of each pipe. Examples of some of the images are shown in Fig. 17. Light areas in these images correspond to regions of low material density. Pipe #1 shows regions where the uranium deposit has flaked off, whereas pipes #2 and #6 show very uniform deposits. The image for pipe #3 shows an extreme case where there is a sudden transition from a region with little deposit (to the right) to a region where the pipe is nearly filled with a uranium deposit. Example K-edge spectra for the different pipes are shown in Fig. 18. In most cases accurate measurements were obtained within a few minutes.

For pipe #3 the very large deposits caused complications for the analysis procedure. A K-edge indication for uranium is clearly present in the spectrum for pipe #3. However, the statistics on the high-energy side of the K-edge are very low, and there are indications from the low-energy portion of the spectrum that there may be significant background under the K-edge. (Based on these observations we are in the process of modifying the detector shielding to greatly reduce this background.)

pipe #1

pipe #2

pipe #3

pipe #5

Figure 15. Photographs of several of the pipes from the K-25 Site UF_6 feed facility which were inspected using the K-edge detector.

Figure 16. Image showing one of the pipes in position for inspection. The X-ray tube is at the left edge of the picture, and the HPGc detector and the real-time X-ray imager are to the right.

pipe #1

pipe #2

pipe #3

pipe #6

Figure 17. Examples of real-time radiographic images for several of the pipes.

For cases such as this we have used a variation of the K-edge technique to obtain a measurement of the uranium contamination. Near the maximum X-ray energy there should be little background in the spectrum. The ratio

$$R_K = I(E_K)/I(E_{\text{end}}), \quad (5)$$

where $I(E_K)$ is the intensity just below the K-edge energy and $I(E_{\text{end}})$ is the intensity near the endpoint of the spectrum, can be used to calculate the amount of uranium present. This calculation will have a slight dependence on the pipe material and thickness. In our calculations we have assumed the pipes to be of monel with 1/8 inch wall thickness.

We have checked this calculation by comparing spectra from pipe #3 with spectra from pipe #6. There is very little uranium in pipe #6, so this can be used as a reference sample to provide a measure of the effect of the pipe itself on the spectrum. Any difference observed in the spectrum for another pipe of the same material and thickness will be due to contaminant materials (i.e. uranium) contained in the pipe. One can then use Eq. 1 to calculate the contaminant thickness, where $I(E)$ is the measured intensity for the sample at a point just below the K-edge energy, and $I_0(E)$ is the intensity obtained at the same energy for a clean reference sample. For pipe #3 this measurement gave results consistent with those obtained using Eq. 5. We have also tested both of these K-edge variations on pipe #2, where the standard K-edge method (Eq. 3) can be used. In this case all three methods give consistent results.

Both of these variations on the K-edge technique will give reliable accurate measurements as long as there is only one dominant heavy metal present. If more than one heavy element is present, the shape of the spectrum becomes more complicated. In principle it would be possible in such cases to obtain estimates for all of the elements present by fitting a model to the entire spectrum. However, such results would be much more sensitive to the presence of background, and would have to be treated on a case by case basis depending on the container material and the heavy elements.

In Fig. 19 we plot the K-edge measurements as a function of position along the pipes. In general we see that the deposit thickness is changing gradually along the length of the pipes and the data can be fit to a linear curve. These fits were used in conjunction with the known circumference of the pipes to calculate the total amount of uranium in each pipe. These results are presented in the first column of Table 1. For pipe #3 the variation is too great to justify a linear fit. We have simply added the contributions from each segment of the pipe. The result for pipe #5 is only for a 20 inch segment at one end of the pipe, and is based on a single measurement.

We have also inspected a brass valve obtained from the same feed facility. The structural material at the center of the valve was so thick that we could not obtain a statistically significant K-edge measurement in a reasonable amount of time. Therefore, we can only give an upper limit on contamination in this valve. A radiographic image (Fig. 20) shows the basic structure of the valve, and indicates that there are no large uranium deposits present.

These same samples were also inspected using a baseline NDA technology[9]. In this technique, passive measurements of gammas from radioactive decays of the uranium are made. A typical data collection time is 1/2 hour, and an additional 15 minutes of analysis is required to make corrections for sample geometry and material. The NDA results are shown in the second column

of Table 1, and are in good agreement with the K-edge measurements. The accuracy for these NDA measurements is estimated to be 30% [10].

Figure 18. Typical K-edge absorption spectra for the pipes.

Figure 19. The contamination distribution along each of the pipes.

Table 1. Amount of uranium contamination in each of the samples.

	K-Edge inspection (grams)	NDA technique (grams)
Pipe # 1	72 ± 7	78 ± 23
Pipe # 2	259 ± 15	342 ± 103
Pipe # 3	806 ± 104	1000 ± 300
Pipe # 5	5.8 ± 3	2.54 ± 0.76
Pipe # 6	6.2 ± 3	5.9 ± 1.8
Valve # 8	< 3.3	0.72 ± 0.22

Figure 20. Real time radiographic image of a valve.

We have previously demonstrated the reproducibility of K-edge measurements for uranium contamination $< 50 \text{ mg/cm}^2$ [2-4]. To verify that this is valid for thicker uranium deposits, we have made repeated measurements on pipe # 1. We placed pipe # 1 in the X-ray beam with the X-ray generator set at 180 kV and 2 mA and the data acquisition time at 60 seconds. As shown in Fig. 21 the distribution of the measured values is consistent with a normal distribution with standard deviation determined by measurement statistics.

The insensitivity of the K-edge measurement to the surrounding environment is one of the attractive features of this technique. As contamination with heavy elements exists in a variety of different environments and geometries, it becomes more difficult to account for the effect of these different environments on the accuracy of NDA measurements. The K-edge technique on the other hand, is not sensitive to the type and geometry of the surrounding materials as long as enough photon statistics can pass through the contaminant and into the detector. We have

demonstrated that the K-edge technique is not sensitive to surrounding conditions by placing pipe # 1 in the X-ray beam and adding different materials. From Fig. 22 it can be seen that consistent results are obtained for a wide range of surrounding materials.

Figure 21. Reproducibility of the K-edge measurements of a uranium-contaminated pipe.

Figure 22. The insensitivity of the K-edge technique to the surrounding environment.

5. Range of Applicability

In the measurements described above we have demonstrated a wide range of applicability of the K-edge technique for measuring uranium contamination. This range is basically limited by the statistics of the accumulated spectra. For very thin deposits we need enough statistics to distinguish the K-edge step from natural fluctuations in the data. As the thickness of the heavy metal or the surrounding container becomes very large, there will not be enough statistics, first on the high-energy side of the K-edge, and, for even thicker amounts, also on the low-energy side, to obtain an accurate measurement. In the first of these cases, one of the variations on the K-edge technique (using a reference sample, or measuring the ratio $I(E_K)/I(E_{end})$) can be used to extend the range.

We summarize these limitations in Fig. 23 for uranium in steel. Using the prototype K-edge system one can obtain measurements with at least 10% accuracy within 15 minutes for the range of values between the lower curve and the dashed curve. Using one of the variations on the K-edge technique, the upper range can be extended to the upper curve. As one moves away from the boundaries towards the center of the plot, the measurement time required to achieve a given accuracy will decrease.

Figure 23. Range of applicability for K-edge measurement of uranium in steel. An accuracy better than 10% can be achieved within 15 minutes for concentrations between the lower curve and the dashed curve using the standard K-edge technique. This range can be extended to the upper curve by using the modified K-edge technique.

This analysis can be extended to other container materials and contaminants. Since the density of monel is similar to that of steel, the range for monel is very close to that for steel. In general, the range will be determined by where the K-edge energy of the contaminant is relative

to the absorption properties of the container. As the atomic number of the element decreases the K-edge energy decreases, and the ability of the corresponding X-rays to penetrate materials decreases. For a lighter contaminant like Cadmium (K-edge at 26.7 keV) it will be difficult to obtain sufficient statistics to make a K-edge measurement for samples in steel containers.

6. Summary and Conclusions

We have demonstrated that K-edge densitometry is a fast, accurate characterization technique for quantifying heavy metal contamination in a variety of situations. We have constructed a mobile inspection device suitable for making in-situ measurements. The operation of this system has been successfully demonstrated on uranium-contaminated samples from the Oak Ridge K-25 Site Gaseous Diffusion Plant. The results obtained are consistent with those from the baseline NDA technology.

Several important characteristics of the K-edge technique were verified during the field demonstration. These include:

- Insensitivity to matrix materials and geometries.
- No sample preparation is needed.
- Good accuracy compared to NDA technique.
- Good spatial resolution for mapping out contaminant distributions.
- Fast, in situ characterization technique.

This field demonstration was an important step in the development of portable K-edge inspection technology. With this experience we are making modifications to the system to make it easier to use and more robust. Shielding improvements will reduce the background and make it easier to determine when the modified K-edge technique should be used in place of the standard calculation. The modified calculations, now done off-line, will be incorporated into the data acquisition software. Based on the results of this demonstration, we feel that the K-edge technology is ready to be applied to a wide range of characterization problems.

7. Acknowledgments

We would like to thank the many people at the Oak Ridge K-25 Site who assisted us in carrying out the field demonstration. We especially thank the staff at the Materials and Chemistry Lab for providing the facilities and support which enabled us to complete this work. We particularly appreciate the efforts of Bob Fellows in serving as our principle contact at Oak Ridge and coordinating the many activities necessary to prepare for our demonstration. We also wish to thank Richard Hagenauer of the NDA group for providing the uranium calibration samples and for performing the NDA measurements for comparison purposes.

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