Development Of A High Sensitivity Monitor For Radionuclides Characterization

Final Report
August 1995 - April 1996

June 1996

Work Performed Under Contract No.: DE-AR21-95MC32090

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
NeuTek.
13537 Scottish Autumn Lane
Darnestown, Maryland 20878-3990

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P.O. Box 880
Morgantown, West Virginia 26507-0880

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13537 Scottish Autumn Lane
Darnestown, Maryland 20878 - 3990

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I. Executive Summary:

The Department of Energy (DOE) is undertaking a major task to clean up the nation's nuclear related facilities and sites, operated by or for the Department. Of the many environmental hazards found at these locations, radioactive contamination poses a special challenge. Radionuclides such as transuranic elements or fission products, in particular constitute serious health threats. Characterizing these contaminations requires either complicated laboratory procedures with accompanying long turn-around time measured in days or weeks or the use of in-situ hand monitors which is equally labor intensive and compromises detail and/or accuracy. Often multiple instruments or techniques have to be used to detect the different types of radiation.

In the base phase of this Research Opportunity Announcement (ROA) program to develop a high sensitivity monitor for radionuclides the feasibility of applying a new radiation imaging concept developed for medical research was examined. The concept utilizes sensors with storage photostimulable phosphor (SPP) technology as radiation detectors. They are applicable to all types of radiation including tritium and their imaging capability can be used to locate and identify 'hot' spots. The renewable thin plastic-like SPP sensor plate can be used directly as a radiation detector or as a high resolution (down to 25 μm) digital imaging sensor in radiography or tomography. The technique is simple to use, expose and scan and one scanner can support many sensor plates. This allows the deployment of multiple sensor plates simultaneously to increase the area of coverage. The digital image of the radiation distribution in the measured area generated by the PC-based scanner lends itself to ready analysis and can be interfaced to a global information system or other DOE data base. The technique can be used either in-situ or in a mobile-lab setting. Tests have found that radiation at regulatory levels can be measured accurately in minutes. For areas with possible neutron contamination, a neutron to charged particle converter screen, such as a dysprosium foil can be used with these sensors.

The high sensitivity (single alpha particles can be observed) and simplicity (expose and scan, one instrument for all types of radiation) of the SPP technique can significantly reduce the time and cost required for many site characterization and environmental monitoring tasks. Although current commercial SPP systems are designed for low energy x-ray imaging or autoradiography from beta-emitting radioactive labels used in medical/bio-medical research, the base phase effort has demonstrated that with some modification the technology can be extended to meet DOE needs. It has been shown that radioactivity from environmental samples as well as from uranic, transuranic elements can be measured quickly, accurately and economically. The types of radiation studied include alpha, beta, gamma-ray and neutrons. A standard operation procedure was illustrated in the preparation and analysis of samples from different types and levels of contaminated soils.

While the SPP sensor plate measurement time for regulatory level of radioactivity is near 'real time', the 2-5 minutes of scanner read-out time for each sensor plate with the current commercial equipment becomes a bottle neck for screening a large area quickly. Depending on requirements, the solution can be in two ways: 1. Instead of complete coverage of the area being monitored, sampling methods can be used; or 2. Since for most applications other than in radiography or tomography extremely fine spatial resolution is not necessary using coarser spatial

resolution by enlarging scanner laser spot size can speed up the scanner process considerably. A read-out speed of 10 seconds or less can be expected when the pixel size is increased to 2.5 cm x 2.5 cm for general decontamination and decommissioning (D&D) or soil measurements. This 'de-tuning' process will increase the area coverage rate for each scanner unit from about 20 ft²/hour to over 400 ft²/hour and will reduce the estimated cost of \$10 per square foot of *actual* sample area using the current commercial equipment to half or less. These alternatives will be examined in the next phase of this program. The one year plan for the next phase will also include other hardware and software improvements to optimize system performance, the setting up of reference standards for system calibration and measurement quality control and the assembly of a transportable unit for extensive field tests.

II. Merits of the SPP Technology:

As demonstrated in the base phase evaluation, the SPP technology shows great potential that it can be developed into a low operating cost, high sensitivity large area monitor system for environmental radioactivity or site characterization before and after clean-up. A site can be quickly surveyed with multiple imaging plate sensors in situ to locate possible contaminated area and show radioactivity distributions. The identified areas can be further examined using three-IP-sensor detectors or by the filter method to distinguish the various radioactive components. The SPP technology offers the following advantages:

- can be used in-situ or as a highly mobile system;
- highly sensitive, is capable of imaging single alpha particle effect, can be used to measure all types of ionizing radioactivity, including tritium. Alpha activity of 100 dpm/100 cm², beta activity of 0.1 dpm/mm², low energy neutron flux of 5 n/cm²s and gamma/x-ray level of 10 µR/hr can all be detected in about 10 minutes;
- energy sensitive, can identify radionuclide through energy differentiation;
- single imaging sensor plate size can be as large as 35 cm x 43 cm, is capable of mapping concentrations of radioactivity such as 'hot' particles, high spatial resolution (down to 25 µm) can be used for digital radiography and computerized axial tomography;
- wide dynamic range with linear response, can be used in high background area for quantitative analysis and digitized output lends itself for ready image and data processing;
- low secondary waste generation, very thin polyester film can be used for contamination barrier when contact measurements of radioactive samples are required, SPP sensor plates are re-usable;
- low operating cost, large area coverage, quick turn-around time and one reader can support many renewable SPP sensor plates;

- quick implementation of the technology, once the performance characteristics are calibrated a laboratory system or field transportable unit can be assembled quickly by using mostly off-the-shelf components, also a microprocessor based portable/remote operable unit can be designed using currently available technology;
- potential for wet application, having a protective polyester cover the SPP sensor plates are moisture resistant and do not require dark room setup.

III. Background:

During the mid-'70's the medical film industry began to develop new imaging media as possible film replacement and to investigate ways to integrate computer image processing to reduce patient exposure. The Kodak and Fuji Company studied the phenomenon of photostimulable luminescence and developed storage photostimulable phosphor (SPP) imaging sensors. These sensors were more sensitive than conventional x-ray films and its high resolution was seen as a way to introduce computerized digital radiography. The SPP concept involves radiation-caused trapping in a phosphor coated detector plate when it is exposed to radiation and release of the trapped energy as light when the detector is stimulated under scanning in a reader with a He-Ne laser beam. A photomultiplier tube detects the light and coordinates the light intensity with the scanned positions, creating a digital image of the radiation field. The light intensity is linearly proportional to the radiation level received over a dynamic range of greater than 10^5 . After scanning, the detector can be renewed by exposure to UV light. The most practical combination of 'color center', the radiation trapping material such as Europium and the light-generating rare earth phosphor Barium was not used until in the mid- or late '80's. The new generation of SPP imaging sensor plates and reader have greatly enhanced performance and have received wide acceptance in bio-medical research¹⁻⁴ for assaying samples labeled with beta-emitting isotopes such as ^{13}C and ^{31}P . It offers 10 to 100 times more sensitivity compare to the traditional film autoradiography and the wide linear response range improves the accuracy of quantitative analysis. It is reported that 0.2 dpm/mm^2 of beta activity from ^{31}P can be detected with one hour exposure and a sensitivity of $1.3 \mu\text{R}$ for 80 kV x-rays is also claimed. Commercial SPP equipment designed for use in bio-medical research and x-ray radiography are available from Fuji and Molecular Dynamics Inc.. SPP systems are available with spatial resolution ranging from $200 \mu\text{m}$ to $25 \mu\text{m}$ and single imaging sensor plate (IP) sizes ranging up to $35 \text{ cm} \times 43 \text{ cm}$. Typical sensor plate costs around \$500 each and with care can be re-used for more than a thousand times.

NeuTek began independently to investigate the possibility of applying the SPP technology for environmental radiation monitoring and alpha particle detection in 1993. For environmental monitoring, the two-step process (exposure and reading) involved in the SPP application may prove to be advantageous. Multiple IP sensors can be used to cover a large area of interest, or to assay a group of samples simultaneously. After a short time of exposure the sensors can be collected and taken to a data reading station for reading. The reading station consists of a computer and a laser readout unit which in its current configuration resembles a desk-top copying machine. The station can be made transportable by placing it in a small vehicle or mounted on a cart. The reading process takes about two minutes per plate depending on plate size with present commercial equipment. After

reading, the sensors can be renewed in a commercial eraser UV box or by exposing them to sun light or strong room light. A commercial eraser box can accommodate 4 sensor plate simultaneously. The cleaning time required ranges from 5 minutes in a eraser box to about 30 minutes under strong room light.

This ROA program will benefit from NeuTek's effort to study the distribution of radioactivity in selected NIST standard reference materials (SRM) for environmental radioactivity. NeuTek is also under contract with the Department of Commerce to develop a high resolution area detector for thermal/cold neutrons, again based on the same sensor technology.

IV. Base Phase Technical Objectives:

The base phase work included an analysis of the characteristics of the new SPP sensor technology and experimental work to demonstrate its capability for quantitative analysis of radioactivity from environmental samples.

The specific tasks for the base phase include the following:

- Conduct measurements of SPP sensor responses to alpha, beta and gamma radiation using NIST standard sources to determine the sensitivity of the technology to charged particles and other radiation emitted from transuranic elements and fission products. This includes, but is not limited to, detection limits, establishing measurement parameters, dynamic range, sensitivity, spatial resolution and reproducibility of the SPP sensor technology.
- Examine and select the optimum filter materials for radiation identification using the energy differentiation property of the SPP sensor technology. Then design a mask with multiple zones using the selected filter materials for radiation characterization.
- Evaluate the SPP system performance against other types of radiation monitoring devices including, but not limited to, electret ionization chamber and alpha track detector, gamma and beta scintillator detector and solid state detectors. The evaluation shall be carried out either by direct head-to-head comparisons or by analysis of the best information available on the performance characteristics for the other types of radiation detectors. Develop a preliminary standard operating procedure (SOP) for application of the SPP sensor technology at DOE sites.
- Conduct additional tests of the SPP technology on contaminated soil samples from a DOE site or on NIST SRM for environmental radioactivity and compare results to radiochemical and other analytical methods.

V. Base Phase Results:

1. Characterization

The SPP technology has been applied to measure the radioactivity strength and distribution of the following NIST standard reference sources:

Alpha: ^{148}Gd , ^{208}Po , ^{229}Th , ^{232}U , $^{235}\text{U}/^{238}\text{U}$, ^{238}Pu , ^{239}Pu , ^{241}Am , ^{243}Cm
Beta: ^{32}P , ^{90}Sr , ^{147}Pm , ^{204}Tl
Gamma: ^{60}Co , ^{57}Co

The SPP IP sensors are high spatial resolution 2-D large area radiation imaging devices. When exposed to a radiation field they will record the detail intensity distribution of the field. Figure 1 shows a SPP image of a large area and three 'point' ^{238}Pu sources. Figure 2 shows an image of three beta emitters. The SPP sensors respond linearly to all types of ionizing radiation. Even low energy beta particles from tritium can be measured. They exhibit a dynamic range of more than five orders of magnitude. This is demonstrated in the measurement of the attenuation of beta particles emitted from ^{147}Pm through various thicknesses of MYLAR (Figure 3). The SPP sensor system measures radiation in units of photostimulable luminescence (PSL) that can be converted to more conventional radiation units using calibration standards. Because the SPP response is energy dependent, it is possible to relate the result to dosage. Figure 4 shows that SPP sensors also respond linearly with exposure time. Some of these measurements were conducted over a period of five months, indicating the excellent repeatability and stability of the SPP sensor system.

The SPP sensors are sensitive enough to register the effects from cosmic rays and ambient terrestrial radiations can be detected in just a few minutes. Since the SPP sensors respond linearly to radiation and have a dynamic range over 5 orders of magnitude they can be used in relatively high background area. A test has shown that the sensors can still maintain a $\pm 10\%$ measurement accuracy of the alpha activity of a ^{238}Pu source (1,500 dpm/100 cm²) in a high gamma background that reduces the signal to noise ratio (SNR) to 1/100. In many applications the needs for conducting background measurements can be reduced by placing test samples in a shielding box to isolate their effect. A shielding box can also enhance the detectability of very low radiation levels in environmental samples. A transportable shielding box was constructed with 10 cm thick lead walls and lined inside with 2 mm copper sheets. Figure 5 shows the effects of such a lead box on the background levels recorded by SPP sensors.

The detectability for alpha emitters ranges from 0.03 Bq (disintegration per second) for ^{148}Gd with alpha energy of 3.18 million electron volts (MeV) to 0.01 Bq for ^{243}Cm with alpha energy of 6.00 MeV. The sensitivity for beta particle emitters ranges from 0.23 Bq for ^{147}Pm ($E_{\text{max}} = 0.224$ MeV), and 0.06 Bq for ^{204}Tl ($E_{\text{max}} = 0.763$ MeV), and 0.02 Bq for $^{90}\text{Sr}/^{90}\text{Y}$ twin with $E_{\text{max}} = 0.546$ MeV/2.270 MeV to 0.001 Bq for ^{32}P ($E_{\text{max}} = 1.711$ MeV). For ^{60}Co , with gamma rays of 1.332 MeV and 1.173 MeV the sensitivity is 0.14 Bq. These sensitivities were calculated assuming the SPP system operating in a gross counting mode and a sample area of 1 cm² was used. A measurement time of one hour and a detection threshold with a SNR of 1:1 were also assumed. Since the SPP

imaging system has spatial resolution as fine as 25 μm , the sampling area can be conformed to the actual source size to improve detection sensitivity and/or measurement statistics. Experiments with soil samples contaminated with ^{238}Pu or natural uranium in the 7 to 20 pCi/g range have indicated that gross activities in the samples can be measured by the SPP method when the SNR is as low as 1/8. In general, the uncertainty in the measurement with SPP sensors is dominated by counting statistics. However, in cases of low level measurement a built-in uncertainty of $\pm 0.002 \text{ PSL/mm}^2$ mainly due to the digitization process is observed. In practical terms, the uncertainty would be about $\pm 10\%$ for an hour measurement of an alpha field of 100 dpm/100 cm^2 .

For even lower alpha activity level a signal processing method called "grain counting" that analyzes the shape and strength of each pixel in a SPP sensor can be used to improve SNR and enhance detection sensitivity by an order of magnitude or more. This technique can be used to discriminate alpha signals against other radiations. One feature of the SPP technology is that it is not only very sensitive to all types of radioactivities but it can also provide an image of the radioactivity distribution. The SPP sensor can detect single alpha particles by providing a cloud chamber type of images of the tracks left by each individual alpha particles (Figure 6, reproduced from Figure 2 of the ROA technical proposal of this program). A single alpha particle will form a cluster or track of 8 to 20 affected pixels (100 $\mu\text{m} \times 100 \mu\text{m}$ pixel size or 0.01 mm^2) depending on the energy of the particle and its incident angle on the SPP imaging sensor. Normal background from cosmic rays or terrestrial radiation generates one- or two-pixel spots. Therefore, for extremely low level alpha (down to few alpha/ cm^2/hour) measurement one might use the SPP technique in a "grain counting" mode that recognizes each individual alpha mark. An analysis of the shapes and the depths (SPP image pixel intensity level) of pixel clusters in SPP images caused by the natural background and those from a NIST ^{238}Pu source has been conducted. Figure 7 and 8 present the results of the analysis by plotting the number of grains (pixel clusters) as a function of the grain size (number of pixels) and the pixel intensity level. The different lines in the Figures indicate different pixel intensity levels.

These Figures show that the signals from the alpha particles are clearly different from the background. The background produces pixel cluster sizes in general less than eight or nine pixels while each alpha particle would produce a greater pixel cluster size. It is anticipated that with the application of this image processing technique SNR of low level radioactivity measurements can be improved by a factor of 10 or more. With a finer spatial resolution (25 $\mu\text{m} \times 25 \mu\text{m}$ pixel size) the SPP system will be able to differentiate not only the alpha particles but beta particle effects as well by using the grain counting technique.

Another test was carried out to confirm the sensitivity of SPP sensors to beta particles and to demonstrate how the new sensor can be used for neutron detections^{5,6} as well. A dysprosium (Dy) foil was activated in a cold neutron (neutron with energy less than 0.05 electron volts (eV)) beam and the decay history of the foil was subsequently traced. A commercially prepared 125 μm thick dysprosium foil about 1.5 cm x 1.5 cm in size was exposed to a cold neutron beam with a thermal equivalent flux of $3 \times 10^7 \text{ n/cm}^2\text{s}$ for 30 seconds at the NIST Cold Neutron Research Facility. Figure 9 shows the logarithm of the fraction of radioactivity remaining in the dysprosium foil as a function of time. In the Figure, $I(t)$ is the relative radiation strength of the foil at time t after the neutron activation as recorded by a SPP imaging plate and $I(0)$ is that at the end of neutron activation. The

imaging plate exposure time was set for 5 minutes for $t < 30$ hours and 20 minutes for $t > 30$ hours except that for $t = 40$ hours which was integrated for 1 hour. All data were normalized to a 5 minute imaging plate exposure time for the graphing. The radioactivity strength was expressed in the internal unit PSL of the SPP imaging plate reader per 1 mm^2 area of the foil. The thermal/cold neutron activation of Dy produces a relatively short-lived (half-life 1.26 minutes) metastable state of dysprosium-165 ($^{165\text{M}}\text{Dy}$) and the dysprosium-165 ground state (^{165}Dy) with a half-life value of 2.35 hours. Both ^{165}Dy and $^{165\text{M}}\text{Dy}$ decay by emitting beta particles. All data was within 1% of predicted decay values except that for $t = 36.2$ hours and 37.5 hours, which were within 5%. The larger errors were probably caused by poor contact of the foil with the imaging plate. The excellent agreement of the SPP measured ^{165}Dy decay with the theoretical predication underscores the sensitivity, linearity and precision of the SPP technology.

Figure 10 shows the SNR as a function of time in the tracking of the Dy foil decay using a SPP sensor. The time is expressed in units of ^{165}Dy half-life. The time of 40 hours represents about 17 half-lives or a decay factor of more than 130,000 for ^{165}Dy . Figure 10 suggests that at 18 half-lives after activation (a decay factor of more than 260,000), the remaining beta activity in the Dy foil could still be measured with a extrapolated SNR of 5. The Dy foil was activated in a thermal neutron equivalence flux of $3 \times 10^7 \text{ n/cm}^2\text{s}$ for 30 seconds and generated an estimated ^{165}Dy radioactivity of $2 \times 10^4 \text{ dpm/mm}^2$. After decaying for 18 half-lives, the remaining ^{165}Dy radioactivity in the foil would be about 0.08 dpm/mm^2 and equivalent to that of a foil at the end of a 30 second activation with a neutron flux of $1 \times 10^2 \text{ n/cm}^2\text{s}$. A foil exposed to a neutron flux of $1 \text{ n/cm}^2\text{s}$ for about one hour will also generate a similar ^{165}Dy radioactivity. This test demonstrates that the SPP sensor system when coupled with a proper neutron to charged-particle converter can function as a very high sensitivity large area neutron detector. Simple metal foils can be placed in neutron contaminated area. After a short time the foils can be collected and placed in contact with SPP sensors to register the neutron effects.

2. Filters

Because alpha, beta particles and gamma rays have very different penetration characteristics in materials, they can be distinguished by inserting various filters in front of a SPP sensor. The sensor system, in addition to possessing the capability of imaging individual alpha particle effect, has the potential to identify various alpha emitters through energy differentiation. Figure 11 shows the results of a transmission test with various alpha sources from NIST. The normalized transmitted responses of the SPP sensor plate to the various alpha emitters is plotted as a function of MYLAR thickness. The filter material used was DuPont MYLAR polyester film. The attenuation curves follow a well known pattern (Bethe's formula⁷) where lower energy alphas were being filtered out faster. Notice that the response of ^{241}Am is very similar to ^{238}Pu , both emitting alpha particles with energy around 5.5 MeV. However, ^{241}Am also emits a higher percentage of x-rays and shows an appreciable residual spectrum compared to ^{238}Pu . ^{243}Cm also shows a residual spectrum from radiations other than alpha. Figure 12 shows the same test with two ^{238}Pu sources and one ^{239}Pu source. The two ^{238}Pu sources differing in strength by a factor of 150 show the same response while the ^{239}Pu with an alpha energy around 5.1 MeV shows a steeper attenuation. Figure 13 shows the same type of test with two depleted Uranium samples designated AA101 and AA102. The two

samples exhibit different concentrations of residual radiations. After the residual spectra have been subtracted, the attenuation curves of the two samples, AA101-X and AA102-X merge. The resultant curve would fit in between that of ^{208}Po and ^{148}Gd in Figure 11, indicating that the main alpha activities in both Uranium samples were of ^{238}U . The attenuation characteristic of each alpha source in MYLAR can be described by its P value, defined as

$$P = (\text{Ln}(A_x/A_0))/x \quad \dots\dots\dots (1)$$

where Ln is the natural logarithm and A_x denotes the activity of the source measured by the SPP sensor with a MYLAR filter of thickness x in μm . Figure 14 shows the P values of the various alpha sources tested as a function of emitted alpha particle energy. These characteristic attenuation curves can serve as references for identifying unknown alpha emitters.

The energy sensitivity of the SPP system to beta particles was also tested and the results presented in Figure 15. The Figure shows the same high sensitivity and linearity of the SPP IP sensors to beta particles as to alpha radiation.

A simpler approach to screen the different types of radiation has been designed without sacrificing the imaging capability of the SPP method. Three SPP IP sensors were stacked together with a 0.4 mm thick copper sheet placed in between the second and the third IP sensors. When exposed to an unknown sample, the first sensor registers the combined effects of all types of radiations from the sample. Any alpha particles released from the sample would not be able to penetrate the first IP sensor, which has a thickness equivalent to about 400 μm of MYLAR, to reach to the second or the third IP sensor. Similarly the second IP sensor and the copper sheet will greatly impede any possible beta particles from reaching the third sensor plate while gamma/x-rays with energies above 100 keV will only be attenuated slightly. Figure 16 shows the images of ^{238}Pu , ^{60}Co , ^{204}Tl and $^{90}\text{Sr}/^{90}\text{Y}$ sources registered by such a three-IP-sensor detector. Note the image of a large area ^{238}Pu source shown at the left of the Figure includes an obvious 'hot' spot. Two ^{60}Co images were generated. The exposure time for the unfiltered cobalt source was 2 minutes. The filtered ^{60}Co source had a plastic filter placed in between the source and the detector to block out low energy beta particles emitted from the source. Therefore the images of the filtered ^{60}Co source were caused by the gamma ray portion of the ^{60}Co radiation. The exposure times for the beta sources ^{204}Tl and $^{90}\text{Sr}/^{90}\text{Y}$, and the alpha source ^{238}Pu were all set at 10 minutes. Images formed by the gamma rays from the filtered ^{60}Co source in all three IP sensors show a noticeable decrease in sharpness compared to those formed by the shorter-ranged alpha and beta radiations. The $^{90}\text{Sr}/^{90}\text{Y}$ twin showed an image even on the third IP sensor. This is because of the high penetration power of the beta particles ($E_{\text{max}} = 2.270 \text{ MeV}$) emitted from ^{90}Y . Figure 17 gives a quantitative presentation of the results of the above three-IP-sensor detector tests. The Figure shows that different types of radiation can clearly be differentiated.

It was a pleasant surprise to find that for radionuclide differentiation, in addition to the use of various filters, some sensitivity to different types of ionizations and energies can also be extracted by repeated scanning of the same SPP IP sensor in the reading process. The assumption is that higher energy particles will penetrate deeper into the IP sensing layer and can deposit more energy deeper into the layer. Repeated scanning liberates those deeply trapped signals. Figure 18 shows the ratios

of the SPP signal from the second scanning to that from the first scanning for various isotopes produced by neutron activation. Energies indicated are maximum beta energies released by each isotopes. Figure 19 compares the same scanning ratios of several alpha emitters.

3. Comparison

The Health Sciences Research Division of the Oak Ridge National Laboratory (ORNL) has conducted a field measurements of radioactive contaminated soils using passive alpha detectors. Two types of detectors, electret ionization chambers (EIC) and alpha track detectors (ATD) were evaluated. Compared to the primary approaches currently used for radiologically contaminated site characterization and remediation verification, gamma-ray spectroscopy and radiochemical analysis or other conventional bench top gross alpha counting methods, these passive detectors offer low cost, sensitivity and simplicity. Though not as accurate nor detailed as the present day methods, these detectors can provide information associated with a particular action level in a few *days* compared to *weeks* that are needed now with minimum sample handling and waste generation. In general, EIC are four to five times more sensitive than ATD but ATD can locate 'hot' particles. The SPP sensors, however, on one hand combine the simplicity and low cost of EIC with the imaging capability of ATD and on the other hand offer analytical capability, even higher sensitivity and a turn-around time of a few *hours* or less.

A standard way to measure sensitivity is to calculate the minimum detectable significant activity for a given measurement or deployment time. The minimum detectable significant activity A_I is defined as

$$A_I = \gamma k_\alpha \sqrt{B} \quad \dots \dots \dots (2)$$

Where γ is the coefficient that converts counts into activity and B is the background count. For a 95% confidence level k_α has a value of 1.645.

Figure 20 plots the minimum significant activity as functions of deployment time for EIC, ATD and SPP. The data for EIC and ATD in the Figure are reproduced from their respective DOE TTP program reports (DOE TTP OR143501 and OR158102 reports). The EIC curve is based on ORNL blank soil measurements and the ATD curve is based on measurements of blank soil from the Nevada Test Site. The SPP curve is based on the measurements of yet another ORNL soil sample. The above measurements were all conducted on thick soil samples (infinite thickness for alpha particles). The SPP sensors are estimated to be 10 times more sensitive than EIC and 40 times more than ATD. The SPP sensors were further compared with EIC on measurements of a thin soil sample prepared from the NIST SRM 4533 Rocky Flats (RF) soil. The thin sample was made simply by brushing soil particles onto an adhesive paper to create a mono-grain layer and then sealed with a 1.5 μ m MYLAR cover. The process which took a few minutes minimized the self-absorption effect in the sample for alpha particle measurement. The sample weighs 14 mg and has an area of 25 cm². The RF soil has a NIST certified activity level of about 14 pCi/g, thus the thin sample has an activity of 0.20 pCi. The SPP measurement results of this sample is shown in Figure 21. About 1 Volt/day change in the EIC readings was observed for this sample and the changes due to background was

about 0.75 Volts/day. The EIC reading process has a built-in uncertainty of ± 2 Volts. It is calculated that the minimum measurement time using EIC to detect such an activity level is about 3 days. Figure 22 shows plots of the minimum significant activity based on thin RF soil sample measurements for EIC and SPP. The SPP sensors show 7 times higher sensitivity than EIC. Since the SPP sensors have a much larger active area than either EIC or ATD, these comparisons will favor the SPP sensors even more if bigger samples are used.

The NIST 2π proportional counter has also been used to measure the activity of thin RF soil samples. The counter failed to distinguish a sample with an activity of 0.007 Bq from its background reading of 0.05 Bq. However it was able to measure the activity of a second sample which was three times stronger. The 2π counter is nearly 100% efficient and has very limited energy differentiation capability. It is basically a particle counter and the accuracy is determined by counting statistics. The counter can not be used to measure gamma activity.

The commonly available gamma spectroscopy is another 'non-destructive' method for radioactivity measurement. Precision electronics and liquid helium cooled solid state detector are used. It is sensitive to gamma and x-rays and can identify isotopic composition in contaminants. Its efficiency is relatively low and typically required long counting time for each sample. A gamma spectroscopy was conducted on the thin RF soil samples mentioned above and on a ^{238}Pu spiked thin soil sample. The measurements were carried out with a very well shielded high efficiency intrinsic Ge detector. One week counting time each was needed to confidently determine the gamma components in the soils. As expected most of these gamma rays were from uranium and thorium series in soil. Both the RF soil and the ^{238}Pu spiked sample contained about the same gamma activity per weight. ^{238}Pu itself being an alpha emitter was not detected. Since gamma rays are long range radiation thicker sample will proportionally reduce the counting time required.

The Oak Ridge Office of the Lockheed Martin Energy System is collaborating with us on soil measurements. Their K-25 plant has sent us soil samples spiked with ^{238}Pu and natural uranium. They have conducted liquid scintillation measurements on the activities of ^{238}Pu and natural uranium. It is a radiochemical method in a broad sense and can precisely measure the combined alpha and beta intensity with almost 100% efficiency. It is strictly a laboratory operation and high work skills are required for sample preparation. Typically the turn-around time is in days.

Hand held Geiger-tube or proportional counter type of portable monitors are commonly used in the field. It is easy to use but sensitivity and accuracy are poor, generally for order of magnitude assessment. It is also labor intensive, one man one instrument for spot check only. Other possible radiation monitors or radionuclide analyzers include, x-ray fluorescence spectroscopy and a relatively new method that uses laser for read-out of thin lithium based thermal luminescence detectors (TLD). X-ray fluorescence spectroscopy is a powerful tool for analyzing near surface chemical composition and can be made portable. However, unlike the SPP sensors, the fluorescence method does not measure radioactivity directly and the chemical composition information can be easily masked by non-radiation related matrix problem. The laser TLD holds promise. Its characteristics are quite similar to SPP sensors. Both are sensitive to all types of radiation and can provide large area coverage. Both are easy to operate. But the laser TLD technology is not as well proven as the SPP. Not enough information is available at the present. A side-by-side test of the laser TLD with the SPP

method is planned for the next phase of this program.

4. Soil Tests

As an example of how the new sensor technology can be useful in environmental monitoring of radionuclides, a small amount of the RF soil was sprinkled on a SPP IP sensor using a thin MYLAR as barrier. The SRM certificate states that each bottle of SRM (about 10 g. of soil) typically contains one or two 'hot' particles. Figure 23 shows the image of the soil sample captured by a ten hour exposure with a SPP sensor. A 'hot' spot was detected and a 16-fold enlargement image of that area is shown on the right. A threshold was set that only pixels of relative high values, or areas of high radioactivity are shown. The enlarged image shows that it is a cluster of particles with relatively high radioactivity. The intensity at the center area of the hot spot was measured to be 39 PSL/mm². Figure 24 shows the SPP image of another sample of RF soil from the same SRM, also with ten hours exposure time. At first glance of the image shown on the left of Figure 24, there does not appear to contain any 'hot' spots. An area indicated by the square was selected and enlarged 16 times, again setting the threshold level so that only pixels with the highest relative values in the defined area would remain. The table in the Figure shows the relative radioactivity strength at the five marked positions. The radioactivities at four positions are 'hotter' than the 'hot' spot found in Figure 23, each shows a level 400 times or more above background. It is estimated that an exposure time of 30 minutes or less will be adequate for the detection of these 'hot' spots.

The primary interest in soil measurement is to quantify alpha radioactivities. It is essential to prepare very thin (~10µm) soil samples to minimize the self-absorption effect in detecting alpha activity in soil. Several sample preparation techniques have been examined, including suspending the soil in Collodion and the use of adhesive tape. The adhesive tape method which uses common adhesive tape to hold a single layer of soil particles consistently yields a relatively uniform thin sample. Several thin test samples were prepared with this simple method from the NIST SRM RF soil. These samples have an average effective thickness of 4.2 µm compared to the known average soil particle size of 6 µm., suggesting that soil particles cover approximately 70% of the tape surface. Soil samples measure 2.5 cm x 2.5 cm in size and weigh on average 15 mg each. Figure 21 shows the results of a series of time measurements on one RF soil sample with SPP sensors. The line shown is the least squared linear fit. The 15-minute and 1-hour measurements consist of 10 runs each. The 30-minute and the 4-hour measurements consist of four exposures each. Measurements of the soil sample with SPP sensor plates show an alpha activity of 0.49 Bq/g (13.5 pCi/g), compared very favorably to 0.51 Bq/g obtained by radiochemistry method.

The soil samples received from the Lockheed Martin Oak Ridge Office were spiked with ²³⁸Pu at levels of 19.3 pCi/g and 340 pCi/g, and with natural uranium at levels of 6.93 pCi/g and 231 pCi/g. Three thin composite samples were prepared using the adhesive method described above. Each consists of one low level (19.3 pCi/g) ²³⁸Pu spiked soil sample, one low level (6.93 pCi/g) natural uranium spiked soil sample and one RF soil sample. A blank was also included for every composite sample. Each individual soil sample measures 2.5 cm x 2.5 cm in size and weighs from 13 mg to 41 mg. The results of a series of time exposure measurements with SPP imaging sensors for one composite sample is shown in Figure 25. The SPP measurements of all the thin low level

^{238}Pu and natural uranium spiked soil samples are presented in Figure 26 and 27 respectively. Two thin samples each were prepared on adhesive tapes from the high level spiked ^{238}Pu and natural uranium soils. Figure 28 shows the SPP measurements on these high level samples. To test the effects of thick samples one sample each was prepared from all the ^{238}Pu and uranium spiked soils together with one from the RF soil. Figure 29 shows the SPP measurement results on these thick samples.

The SPP measurements of the various thin ^{238}Pu and natural uranium spiked soil samples are summarized in Figures 30 and 31. The lines represent the least squared linear fit of all the data in each sample measurements. For the convenience of direct comparison the data were normalized for different sample weights to activities per gram of soil. The SPP measurements indicate that the activity ratio between the high and low level ^{238}Pu spiked samples is only 3.6 instead of the assumed value of 17.6 (340 pCi/g / 19.3 pCi/g). For natural uranium spiked thin samples the ratio is 3.4 instead of 33 (231 pCi/g / 6.93 pCi/g). It has been demonstrated that the SPP sensors respond in a linear fashion to different intensities of ionizing radiation. The discrepancies can only be explained by the fact that the un-spiked base soil itself may contain considerable radioactivity compared to the spiked values. Unfortunately, an un-spiked base soil sample was not available for testing. A different approach was taken to check the validity of the measured SPP values by using the known spike ratios.

For the thin high and low level ^{238}Pu spiked samples their normalized activity values in units of PSL for a measurement time of 3 hours are 4106 and 1070 respectively. Both the base soil and the ^{238}Pu that were added contributed to the activities.

$$\begin{aligned} X_1 + Y &= 4106 && \text{.....(3)} \\ X_2 + Y &= 1070 && \text{.....(4)} \\ X_1 &= 17.6X_2 && \text{.....(5)} \end{aligned}$$

X_1 denotes the contribution from the high level ^{238}Pu added to the base soil, X_2 the low level ^{238}Pu that was added and Y the contribution from the base soil itself. The solution to these equations are

$$X_1 = 3218, X_2 = 182 \text{ and } Y = 888.$$

For the thin high and low level uranium spiked samples their corresponding values are 2333 and 960.

$$\begin{aligned} Z_1 + Y' &= 2333 && \text{.....(6)} \\ Z_2 + Y' &= 960 && \text{.....(7)} \\ Z_1 &= 33 Z_2 && \text{.....(8)} \end{aligned}$$

where Z_1 , Z_2 and Y' have similar denotations as in the plutonium case. The solutions to equations 6 through 8 are:

$$Z_1 = 1416, Z_2 = 43 \text{ and } Y' = 917.$$

The fact that the value of Y' is nearly identical to that of Y indicates the same base soil was used for

the two groups of samples. When this approach was applied to the thick spiked samples a similar result was obtained that the contribution from base soils in the ^{238}Pu and uranium groups were within 5% of each other. Again, this indicates that the base soils in the two groups are the same and contribute significantly to the overall radioactivity levels.

The assumption that the same base soil were used in all the samples prepared by Oak Ridge was also tested by conducting filter measurements on the various thin and thick soil samples. ^{238}Pu emits alpha particles with energies around 5.5 MeV. These alpha particles can be stopped with about 40 μm thick of MYLAR. Therefore with the ^{238}Pu spiked samples no ^{238}Pu alpha particles can penetrate the first SPP IP sensor to reach the second or the third IP sensor in the measurement using the three-IP-sensor detector described earlier. The signals registered on the second IP sensor would be the results of the attenuated radioactivity from the base soils. In other words, both the high and low level ^{238}Pu spiked thick samples should leave similar imprints on the second or the third IP sensor. A 51 hour measurement of the ^{238}Pu and uranium spiked thick samples with a three-IP-sensor detector shows the following readings (in units of PSL):

First layer sensor:

37575 for high level uranium;
5188 for low level uranium;
7420 for high level ^{238}Pu ; and
4640 for low level ^{238}Pu .

Second layer sensor:

15022 for high level uranium;
1623 for low level uranium;
1184 for high level ^{238}Pu ; and
1152 for low level ^{238}Pu .

Since the ^{238}Pu activity would be filtered out by the first layer sensor the activity registered on the second IP sensor for the ^{238}Pu samples were from the base soils. The similar readings of 1184 PSL and 1152 PSL for the ^{238}Pu samples show that the same base soil were used in both. If one further assumes that the same base soil was used in all four samples then the uranium activities on the second layer sensor can be extracted by subtracting the base soil activity (average 1165 PSL) from that of the uranium samples:

$(15022 - 1165) = 13857$; and
 $(1623 - 1165) = 458$.

The signal from the high level uranium sample is 30 times stronger than that from the low level one after the subtraction. This ratio is within 10% of the given value of 33. This validates the same base soil assumption and demonstrates the analytical capability of the SPP technique. The extracted activity level for the base soil was compared to that of the RF soil in thin and thick sample configurations and the RF soil level was found to be 1.6 times higher. Both soil types behaved

similarly in three-layer-sensor detector tests and also in MYLAR filtered measurements. This indicates that both soil types have similar proportions and properties of alpha, beta and gamma radiations. Figure 32 shows the results of SPP measurements of the thick soil samples with a three-IP-sensor detector. The curve for the RF soil overlaps that for the low level uranium spiked sample because the spiked amount is very small compared to the activity in the base soil. One also note that except for the high level uranium spiked soil the attenuation rates from the second IP sensor to the third for the other spiked samples all parallel that for the RF soil. In other words, the signals on the second and the third IP sensors for both the high and low level ^{238}Pu spiked samples were from the base soils.

VI. Preliminary Standard Operation Procedures:

1. Apparatus:

The following equipment are needed for SPP radioactivity measurements:

- * SPP scanner reader
- * SPP imaging plates (IP), size 20 cm x 25 cm or 20 cm x 40 cm
- * IP eraser box
- * Optional radiation shielding box
- * 6 cm x 6 cm size paper sample holders with 5 cm x 5 cm adhesive surface in the center
- * 7.5 cm x 7.5 cm x 1.5 μm thick MYLAR sheets
- * Soft watercolor paintbrushes
- * Tweezers and plastic or cotton gloves
- * Set of well characterized reference standards or soil samples

2. Procedures:

2.1. Site Preparation

- 2.1.a. For soil measurement, clear area of grass, rock, etc.
- 2.1.b. Smooth soil surface.
- 2.1.c. For metal surface or concrete, clear debris or any coverings.

2.2. Deployment

- 2.2.a. Renew SPP IP and record IP identification numbers..
- 2.2.b. For in-situ (soil, concrete, metal surface etc.) measurement:
 - 2.2.b.i. Cover an 5 cm x 5 cm area on the IP with a thin lead sheet (about 1 mm thick) to be used as background monitor.
 - 2.2.b.ii. Place the IP over measurement area and record measurement start time.
- 2.2.c. For sampling measurement:
 - 2.2.c.i. To prepare soil sample, weigh an adhesive paper sample holder and record its weight.
 - 2.2.c.ii. Use brush to pick up soil particles and brush onto the adhesive paper

sample holder.

2.2.c.iii. Weigh the soil sample and record its weight..

2.2.c.iv. Cover the soil sample with 7.5 cm x 7.5 cm x 1.5 µm MYLAR.

2.2.c.v. Place up to 15 samples on one 20 cm x 40 cm size IP and record IP identification number and the position for each samples on the IP.

2.2.c.vi. If a shielding box is available place the IP with the samples in the shielding box.

2.2.c.vii. Record measurement start time and leave sample undisturbed for the duration of predetermined exposure time.

2.2.d. Repeat steps 2.2.b. or 2.2.c. for any additional measurement areas or samples.

2.3. Retrieval and IP Reading

2.3.a. Retrieve IP and record the measurement stop time.

2.3.b. Collect all the IP's that have completed the pre-determined measurement time and place them on reader stack.

2.3.c. The time between the end of measurement and actual IP reading should not be more than two hours or less than 15 minutes.

2.3.d. The scanner-reader and exposed IP's should be placed in a low radiation background area.

2.3.e. Set up appropriate scanner-reader parameters on scanner computer and start scanning.

3. Measurement Standards and Calibration:

The SPP scanner readout result of an exposed IP depends on the type or types of radiation and the level of the radiation. To convert the scanner readout in units of PSL a calibration procedure is required. This involves the pre-determination of the type or types of radiation present in the site or samples to be measured. The previous described filter or 3-IP-sensor detector methods can be used in conjunction with other conventional methods in determining the types of radiation or isotopes which most likely would be present in the site or samples. This site or sample-specific information will be used to create site-specific calibration standards. These standards may consist of:

- * Uncontaminated soils samples from the site spiked with different levels of site specific contaminants or contaminated soil samples from the site which have been analyzed for radioactivity. A blank should also be included in the standard reference set.
- * NIST SRM can be blended into suitable substrate materials (stable, durable and no radioactivity) to produce a series of thin reference standards containing isotopes of interest with radioactivity ranging from 10 dpm/100 cm² to 10,000 dpm/100 cm².
- * Exposure the IP's to the set of reference standards under similar test conditions as described in the previous section.
- * Plot the scanner readout of the exposed IP's in units of PSL against exposure time and contaminant radiation level as demonstrated in the soil test portion of the Base Phase Results.
- * Apply linear regress process on the plots and derive a site specific calibration factor in units

of pCi/g/PSL/min. for thin soil sample or pCi/PSL/min for thick soil samples or surface contamination measurement on concrete or metal surfaces.

- * Use the derived calibration factor to convert the results of actual SPP site or samples measurements from the unit of PSL per minute of exposure time to the unit of pCi/g or pCi.

VII. Discussion and Conclusion:

The SPP technology is a proven technology that is widely used in bio-medical applications for imaging beta particles or gamma/x-rays. It is also being used for neutron detection and environmental radiation monitoring. Within the DOE complex, BNL is using it for neutron and gamma/x-ray detections, ORNL for measuring beta particle distributions and Battelle Northwest for health physics radiation dosimetry measurements.

A SPP system has two components, SPP imaging sensor plates and a laser scanner. One scanner can support multiple sensor plates. The sensor plates are made of thin flexible plastic coated with special phosphor materials and are available in various sizes up to 35 cm x 43 cm. The imaging capability of the SPP sensors and its sensitivity to all types of radiation make them suitable for a wide range of applications, including mixed field. For measurement of alpha or beta activities, one or more test samples can be placed on a sensor plate in a mobile laboratory setting or sensor plates can be applied directly on walls or floors for *in-situ* measurements. For gamma or x-ray measurement the SPP sensor can either be used in a direct contact method or as an imaging device in remote sensing autoradiography. The sensor plate can also be used in special non-destructive evaluation (NDE) applications such as dual-energy or K-edge x-ray radiography to rapidly identify uranium or heavy metal contamination in pipes. Because the SPP sensors respond linearly to radiation and have a dynamic range over 5 orders of magnitude they can be used in relatively high background area. A test has shown that the sensors can still measure accurately the alpha activity of ^{238}Pu in a high gamma background that reduces the signal to noise ratio to 1/100. The *exposure* or measurement time required is dependent on the radioactivity level to be measured and the statistical accuracy desired. Afterwards, the sensor plate is inserted into the scanner to read out the radiation distribution information. The scanner is interfaced to a PC type computer for imaging analysis and data processing. A data base can be established to link the digital SPP output to GIS or CAD. Sensor plates are reusable and can be recycled for more than a thousand times. It can be renewed each time by exposing it to strong light or placed it in a UV light box for a few minutes.

A laser scanner can read out a 20 cm x 25 cm standard size sensor plate in 2-5 minutes with spatial resolution as fine as 25 μm . This fine resolution, though in general not used for many D&D or soil measurements, is essential when detailed imaging is required such as in radiography or tomography applications. The fine resolution also serves as a check on the quality of the detector system that its detection efficiency is uniform throughout the entire active area. One important advantage of the SPP technology is that it is a multi-purpose instrument. Not only it is applicable for measuring all types of radiation whether it be for waste management or health physics but it also can be adapted to different usage conditions or be interfaced with different techniques.

The sensitivity and accuracy of the SPP technology were demonstrated in the measurement of low radioactivity level natural matrix soil samples from Rocky Flats. The level was found to be 2 dpm/100 cm² or about 13.5 pCi/g, in very good agreement with a NIST study using radiochemistry method that took more than a month to complete. This high sensitivity ensures that the SPP technology can be applied in many types of D&D or soil measurement tasks to meet current or future regulatory requirements. The restricted release values provided in Table 2-2 of the DOE Radiological Control Manual (DOE 1994) follow the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.86 in stating that the average acceptable surface contamination level for uranium except ²³⁸U is 5000 dpm/100 cm² and for transuranics 100 dpm/100 cm². However, the recently released NRC NUREG-1500 states that to achieve a 15 mrem/year guideline the limit for uranium surface concentration is about 1000 dpm/100 cm² and soil concentration can be no more than 20 pCi/g in a residential scenario. The Technology Programs Division of the Fernald Technology Source and Integration Department indicated in a report on Fernald's Technology Needs (10/94) saying that although not approved, the detection criteria for soils would most likely start at 50 pCi/g. The trend certainly is toward tighter regulatory standards and the need for sensors capable of detecting low level radioactivity will increase.

For uranium surface contamination a level of 350 dpm/100 cm² can be detected in one minute using the SPP sensors and only a few seconds of measurement time will be needed for detecting a level of 10,000 dpm/100 cm². The wide dynamic range and accuracy of the SPP method make it suitable for initial screening and after clean-up verification tasks. While the SPP sensor plate measurement time for such high level of radioactivity is near 'real time', the 2-5 minutes of scanner read-out time for each sensor plate with the current commercial equipment becomes a bottle neck for screening a very large area quickly. In fact, with the sensor plate separated from the scanner unit the exposure time for each individual measurement is irrelevant for area coverage. If a longer exposure time is needed more sensor plates can be used as a compensation to maintain the same area coverage rate. Depending on requirements, the solution can be in two ways: 1. Instead of complete coverage of the area being monitored, sampling methods can be used, for example if 5 cm x 5 cm sensor plates were used for each 100 cm² area then a 10 ft x 10 ft wall area can be surveyed in one hour with a single scanner unit; or 2. A coarser spatial resolution by enlarging scanner laser spot size can speed up the scanner process considerably. A read-out speed of 10 seconds or less can be expected when the pixel size is increased to 2.5 cm x 2.5 cm for general D&D or soil measurements. This 'de-tuning' process will increase the area coverage rate for each scanner unit from about 20 ft²/hour to over 400 ft²/hour. The above alternatives will use existing technologies and requires less than six month development time. NeuTek may seek collaboration with other companies including Fuji to develop and market SPP systems for DOE and other environmental monitoring applications.

The SPP sensor technology has been characterized for monitoring nuclear or environmental radiation. The performance of one type of SPP sensors with BaFBr:Eu²⁺ as phosphor was evaluated using National Institute of Standards and Technology (NIST) calibrated alpha and beta emitters similar to those found in environmental restoration activities. Mixed-field applications have also been conducted to study the effects of filters with these new sensors. A standard operation procedure has been demonstrated in the preparation and analysis of samples from different types and levels of contaminated soils. The SPP sensor system provides high sensitivity and precision to all types of radiation measurements. Uranium and transuranium contamination of levels from about 10 dpm/100 cm² to more than 100,000 dpm/100 cm² can be quantified accurately. Its imaging capability can map

the radiation distribution to locate 'hot particles' or contamination spots to reduce the areas that require treatment, preserving disposal capacity. The sensitivity of the system minimizes turn-around time for measurements, typically in minutes to comply with regulatory requirements. Multiple sensor plates can be used with one scanner unit to provide *complete* area coverage at the rate of 20 ft²/hour using currently available commercial equipment. This coverage rate can be considerably increased either by using a sampling method or by modifying the scanner to enlarge its pixel size. The digital nature of the technology adapts to computerized data management; contamination data and images can be stored permanently on CD-ROM. The estimated cost for applying this technology using currently available commercial equipment is \$10/ft² of *actual* sample area. With a customized system the cost can be expected to decrease by a factor of 2 or more.

Through further experimental work and theoretical confirmation, the optional phases of this program will provide additional information about sensor material and system configuration, in terms of optimum sensor type and thickness, hardware and software field adaptability. This will lead to the development and field tests of a prototype environmental monitoring system for radionuclides, both in transportable and portable/remote operable configurations.

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X. Conferences Attended and Papers Presented:

1. "Storage Photostimulable Phosphor, A High Sensitivity, High Resolution Detector for Radioactivity". Poster at the Health Physics Society 1995 Annual Meeting, Boston, MA, 7/23 - 7/25/95.
2. "Utilizing Storage Photostimulable Phosphor Technology in Radioactively Contaminated Site Characterization and D&D Verification". Invited talk at ER95, Denver, CO, 8/16 - 8/20/95.
3. "Radioactivity measurements using storage phosphor technology". Poster at Environmental Technology Development Through Industry Partnership, Morgantown, WV, 10/3 - 10/5/95.
4. "Radioactivity measurements utilizing storage phosphor technology". Invited talk at the Fourth annual meeting of the Council on Ionizing Radiation Measurements and Standards (CIRMS), Gaithersburg, MD, 11/27 - 11/30/95.
5. "A New-Old Way to Measure Neutron Diffraction and Scattering". Invited talk at the Workshop on the Use of Image Plates in Neutron Scattering, BNL, 2/22 - 2/23/96.

XI: List of Acronyms and Abbreviations:

ATD	Alpha track detector
BNL	Brookhaven National Laboratory
Bq	Bequerel (disintegrations per second)
D&D	Decontamination and decommission
DOE	Department of Energy
dpm	Disintegrations per minute
EIC	Electret ionization chamber
METC	Morgantown Energy Technology Center
MeV	Million electron volts
NDE	Non-destructive evaluation
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PSL	Photostimulable Luminescence
RF	Rocky Flats
ROA	Research Opportunity Announcement
SNR	Signal to noise ratio
SOP	Standard operation procedure
SPP	Storage Photostimulable Phosphor
SRM	Standard reference material
TLD	Thermal luminescence dosimeter

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Figure 4. SPP measurement of Pu-238

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NIST alpha sources

Figure 12. Attenuation in MYLAR

Pu-238 and Pu-239

Figure 13. Attenuation in MYLAR
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Figure 14. SPP Energy differentiation

Figure 15. Attenuation in MYLAR

NIST beta sources

—■— Pm-147, Emax=224keV
 —●— Sr-90/Y-90, Emax=546/2270keV

—▲— Tl-204, Emax=766keV

Figure 16. Images of 3-IP-sensor detector test

Figure 17. 3-IP-sensor detector test
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Figure 18. SPP energy differentiation
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Figure 19. SPP energy differentiation

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Linear fit, all thin U spiked samples

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Thick samples