MCNP-PoliMi Simulation of Neutron Radiography Measurements for Mass Determination for a Trough of UO3

B. R. Grogan, J. T. Mihalczo, J. A. Mullens
Oak Ridge National Laboratory
P.O. Box 2008, MS-6010, Oak Ridge, TN 37831-6010

Abstract

The Nuclear Materials Identification System (NMIS) has proven shown itself capable of accurately determining the mass of fissile material inside of a container using active interrogation with a deuterium-tritium neutron generator. This paper investigated the possibility that the NMIS could be used to determine the mass of UO_3 powder located in stainless-steel trough-shaped containers at the Y-12 National Security Complex. The MCNP-PoliMi computer code was used to model several imaging measurements by the NMIS and estimate how accurately the mass of the UO_3 powder could be determined.

Introduction

The Nuclear Materials Identification System (NMIS) was developed at the Oak Ridge National Laboratory and at the Y-12 National Security Complex for the purposes of characterizing both fissile and non-fissile material. [1] It uses active neutron interrogation to conduct non-intrusive scans. In the past, the NMIS has been used to image the contents of sealed containers and other objects that could not easily be opened and physically inspected. [2, 3] In this paper, NMIS measurements were simulated using MCNP-PoliMi to determine if the system would be useful in determining the mass of UO_3 powder located in containers similar to those located at the Y-12 Complex.

The Nuclear Materials Identification System consists of three components: a neutron source, two or more fast detectors, and computer hardware and software which measures time correlations between the detectors to ~1 ns accuracy. [4] In the modeled configuration, an associated particle sealed tube neutron generator (APSTNG) is used for the neutron source. The D-T reaction in the APSTNG produces an alpha particle and a 14.1 MeV neutron that travel away back-to-back. An alpha detector attached to the DT generator defines a fan of neutrons traveling towards the fast detectors, in the opposite direction of the alpha particles. [5] This fan of neutrons is aimed towards the target of interest and other detectors are placed on the opposite side of the target. The NMIS processor records each alpha particle detected as well as any pulses in the other detectors. It then calculates, in real-time, the time dependent coincidences between the alpha detector and each of the other detectors. [1]

In order to model this NMIS measurement, the MCNP-PoliMi code was used. The PoliMi code was developed from the standard MCNP-4c code. [6] The methods used by the standard MCNP code will sometimes model the physics of a single interaction incorrectly for efficiency reasons. While these methods may produce excellent results when averaged over a large number of particle histories, they are not satisfactory when the measured quantity involves the time-dependent correlation of individual particle histories. [7] MCNP-PoliMi models each neutron-nucleus interaction as closely to physical reality as possible in order to accurately track each particle for time-of-flight measurements. [6]

Simulation

The simulations were modeled using the MCNP-PoliMi computer code. The target of the measurement was modeled as a stainless steel trough-shaped container based loosely on a design in use at the Y-12 Complex. The container walls were 0.95 cm thick and constructed with SS-304L stainless steel. The bottom of the container was rounded with an interior radius of 6.35 cm. Overall, the exterior of the container was 45.7 cm long, 18.9 cm tall, and 14.6 cm wide. Inside of the container was placed a quantity of uranium trioxide powder of unknown mass and density profile. Figure 1 shows a drawing of the container.

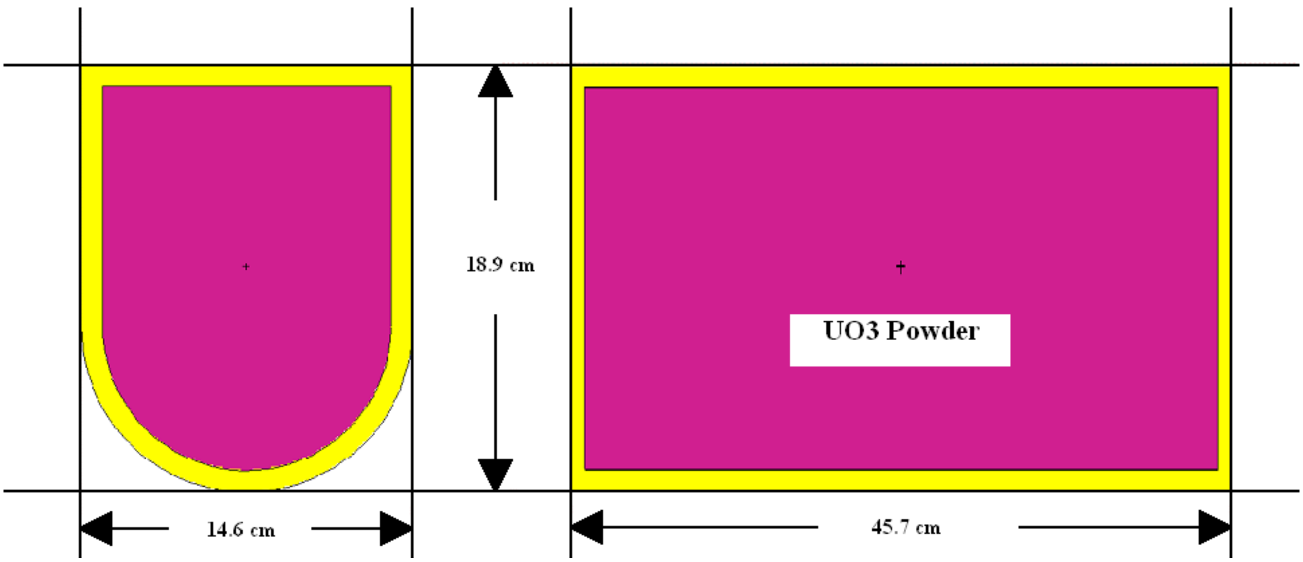

Figure 1. Diagram of the UO_3 trough.

The APSTNG was modeled as a monoenergetic 14.1 MeV neutron source. The neutrons were generated in a fan 45 degrees wide by 10 degrees high, the same as the neutron fan defined by the alpha detector on the physical APSTNG. The centerline of the trough was placed 70 cm away from the source and the front faces of the detector array were placed on a circular arc 156 cm away. Twenty-four 1x1x6" fast plastic scintillators were modeled for each simulation and spaced so that there was one open position between each pair of detectors. A second MCNP-PoliMi run then shifted each detector one position to the left so that the entire horizontal arc of the APSTNG was covered. Vertically, the source and the detectors began approximately 1 cm below the container bottom and they were then raised in 1 cm increments until they were approximately 1 cm above the top of container. In total, there were 2 MCNP-PoliMi runs at each height and twenty-two heights, for a total of 44 PoliMi runs per simulated container measurement. These measurements define a radiograph with 1056 total pixels of resolution. A setup of the problem geometry is shown in Figure 2 below.

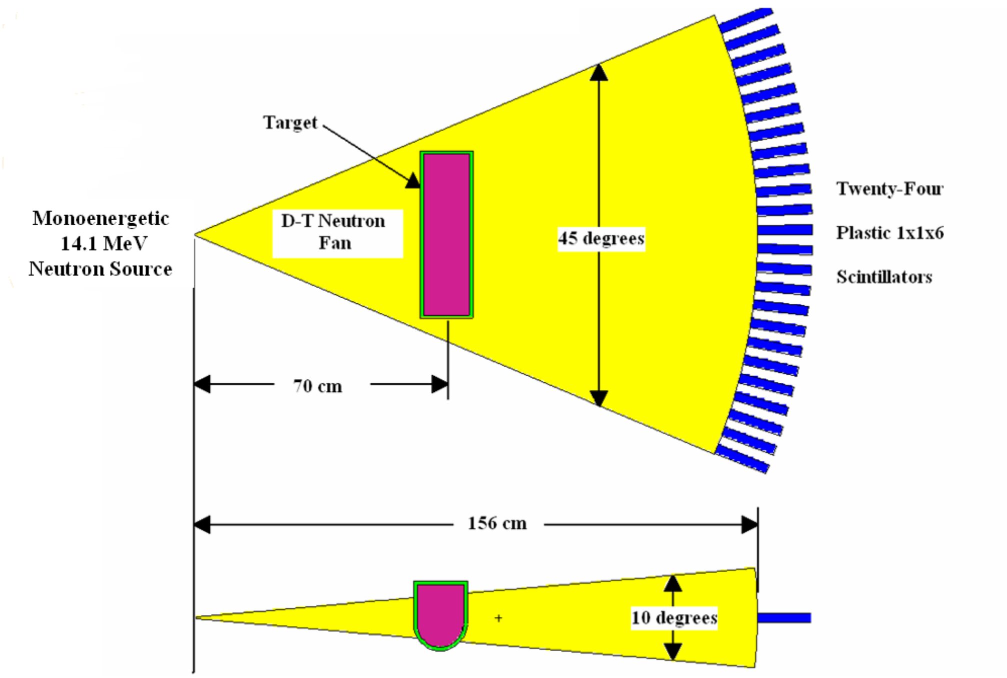

Figure 2. MCNP-PoliMi Problem Geometry.

The APSTNG generates approximately 3×10^7 14.1 MeV neutrons per second isotropically. The modeled D-T fan covered approximately 3.47×10^{-3} of the total solid angle and the alpha detector was assumed to have an efficiency of approximately 85%. [8] This equates to 8.85×10^4 neutrons per second in the neutron arc. In a typical measurement, the NMIS processor gathers 10^7-10^8 blocks of data, with each block consisting of 512 ns of data. In order to match the MCNP-PoliMi simulations with the physical NMIS configuration, each individual simulation was given a source term (nps card) that was an even multiple of 8.85×10^4 X 5.12 sec = 4.53×10^5 neutrons. For 44 measurements, this equates to 225 seconds (3.75 minutes) of total measurement time (excluding the time required to move the source and detectors between each measurement.) Although the NMIS software allows for smaller measurement times, they are impractical in this case because of the hardware movement times.

The first two MCNP-PoliMi measurements taken consisted of two long reference measurements. These two simulated measurements were made for the purposes of determining the neutron transmission through the UO_3 powder as a function of density. The first measured an empty container and the second measured a container with a known configuration of UO_3 powder, in this case completely filled with a density of 8.00 g/cm^3. Each reference measurement had a total of 4.53×10^7 neutrons per PoliMi run. Summed over all 44 detector positions, this is equivalent to a total of approximately 6.25 hours for the entire measurement. The measurements were each broken down into three equal parts. Each part was run with a different random number seed (using the DBCN card) to ensure that the results were not unduly influenced by a single random number. MCNP-PoliMi produced a data file which contained every neutron and gamma collision in the detector cells. The MCNP-PoliMi post-processor was run to extract only those collisions that would produce a light pulse of 1 MeVee (MeV electron equivalent) or greater in a physical detector. [6] These pulses were then correlated with the source particle number to produce a time-correlation graph. Figure 3 shows a typical time-correlation graph which has been normalized to show coincidences per source neutron.

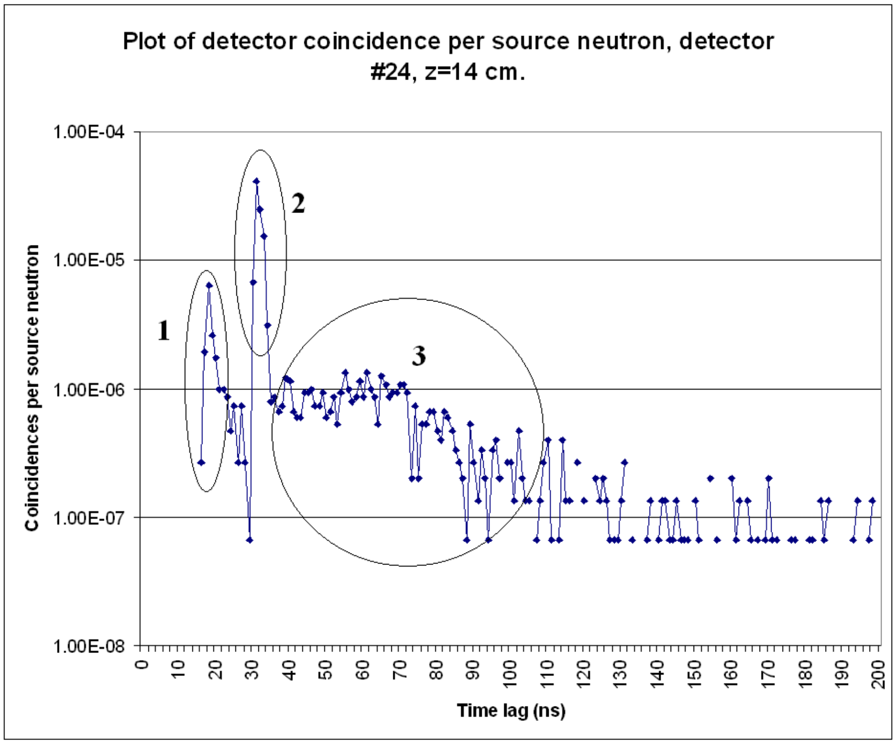

Figure 3. Time-correlation graph of time-dependent source-detector coincidences with three regions of interest labeled.

The time correlation graph in Figure 3 shows several of the features of the D-T source. A 14.1 MeV neutron travels at 5.14 cm/ns. At this speed, the neutrons will reach the container in 13-16 ns. Gamma rays might then be produced by inelastic scattering, (n,γ) reactions, or induced fission, and travel to the detector array at the speed of light, arriving 2-4 ns later. This produces the 15-19 ns peak labeled as 1 on Figure 2. 14.1 MeV neutrons passing directly to the detectors without an interaction arrive at the detectors after 30-34 ns, creating the peak labeled as 2. Finally, the broad peak labeled as 3 consists of neutrons produced by induced fissions as well as source neutrons that have been significantly slowed by scattering.

For the purposes of fast neutron radiography, only those neutrons that passed through the target uncollided, corresponding to region 2 of Figure 3, are of interest. For each of the 1056 detector positions, the area under region 2 from 30-34 ns was integrated to measure the value of I_0 (for the empty container) and I_8 (for the known, ρ=8 case.) With the I_8 and I_0 values known, the neutron transmission was then calculated using the following equation:

$$\frac{I_8}{I_0} = e^{-a\rho} \Rightarrow a = \frac{-\ln\left(I_8 / I_0\right)}{8 \dfrac{g}{cm^3}} \qquad \text{(Equation 1)}$$

The coefficient *a* represents the slope of the natural log of the neutron transmission plotted against the UO_3 density. Note that *a* was calculated separately for each pixel. Figure 4 shows such a plot for a typical detector pixel. Note that because neutrons can elastically scatter off the heavy Uranium nuclei with very little energy loss, slightly scattered neutrons will reach the detector with only a slight delay and will be counted with the unscattered neutrons in the neutron peak. This causes the measured transmission values to be higher than the value calculated using the total cross-sections for the material.

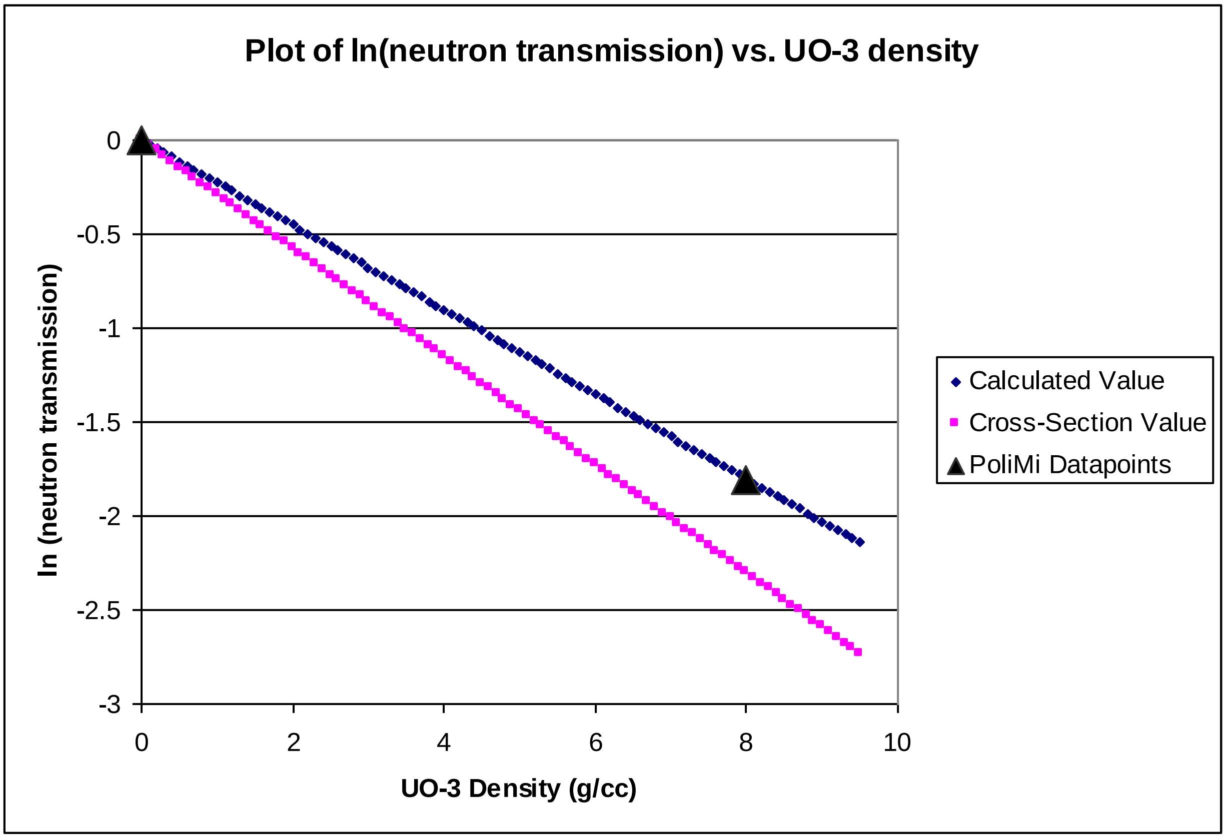

Figure 4. A plot of the natural log of neutron transmission vs. UO_3 powder density.

After the attenuation coefficients were determined using the two reference cases, new MCNP-PoliMi models were constructed for three 'unknown' cases. The three cases were chosen to test the ability of the measurement process to estimate the mass in containers with varying densities, uneven surfaces, or voids in the UO_3 powder. A cross-section of the three unknown cases is shown in Figure 5. The first two test cases were also measured for varying lengths of time to estimate the accuracy that could be expected for a given measurement time.

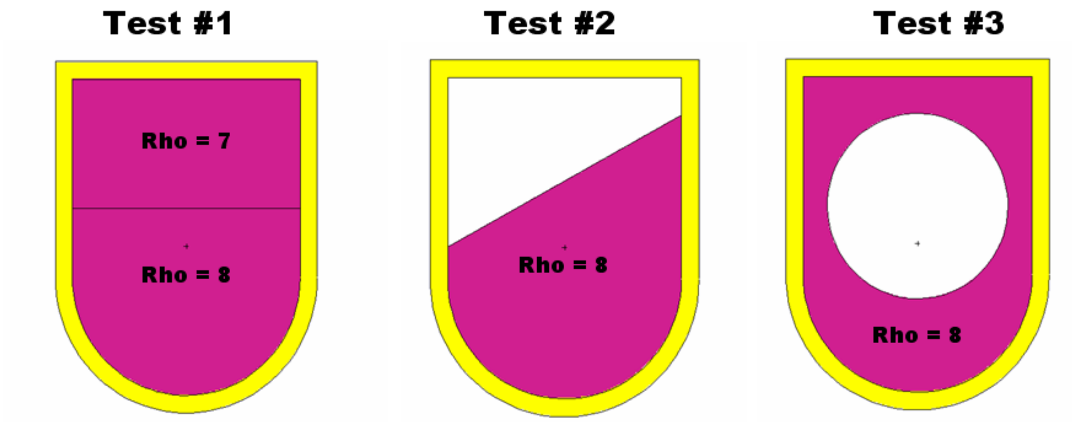

Figure 5. The three test cases modeled in MCNP-PoliMi.

For each unknown measurement, the total number of neutrons in the 14.1-MeV neutron peak was measured exactly as it was for the reference measurements. This value was then divided by the value for the empty container to determine the neutron transmission. Equation 1 was then inverted and average density at that detector position was measured.

$$\rho = \frac{-\ln(I/I_0)}{a} \qquad \text{(Equation 2)}$$

Once the average density for each detector position was calculated, it was multiplied by the volume of the container that shadowed that particular pixel to yield the mass of UO_3. Each of these mass elements was then summed up to come up with the final calculated value for the mass of UO_3 powder. Figure 6 shows the density plot that was created for Test Case #3.

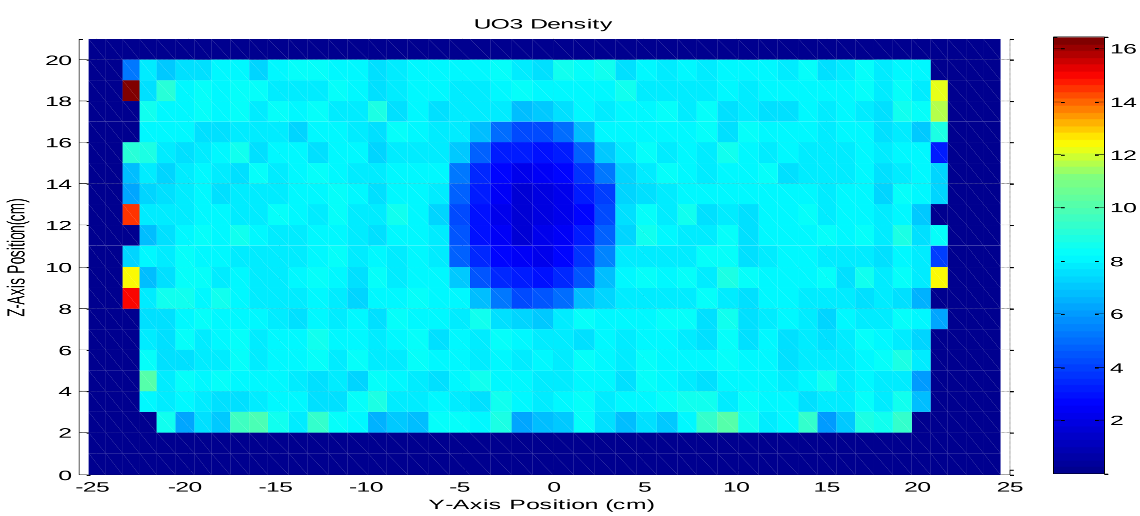

Figure 6. A radiograph of unknown case number three showing the computed density of each pixel

Results

Table 1 shows the results of the seven different unknown measurements conducted. The number of the test indicates the container configuration and the letter indicates the length of measurement time.

Test Number	Measurement Time (min)	Modeled Mass (kg)	Estimated Mass (kg)	Estimate Error (%)
1a	3.75	65.567	65.7	+0.16
1b	15.02	65.567	66.4	+1.30
1c	37.55	65.567	65.9	+0.55
2a	3.75	45.339	45.2	-0.23
2b	15.02	45.339	45.4	+0.19
2c	37.55	45.339	45.0	-0.72
3c	37.55	65.222	64.8	-0.64

Table 1. MCNP-PoliMi simulated measurement results.

Conclusions

Despite the different measurement times and powder configurations, all of the simulated measurements produced a UO_3 mass estimate that was within 1.5% of the true value. Longer measurement times did not produce more accurate results within the range of times modeled. This is most likely because of the algorithm used to determine the mass of the container. A pixel in one of the long test cases (the ‘c’ tests in the table above) typically received 3-400 counts during the test, which would yield a random fractional error of ~5%, but summing them together tends to cancel out the random statistical fluctuations in individual pixels. Over the entire volume of the trough, approximately 300,000 total counts were recorded, which would yield ~0.2% fractional error. Systematic errors, such as volume element errors involving the resolution of the pixels are on the order of the random fluctuations in the data even for the shortest measurement times.

In an actual NMIS measurement, there will be many additional sources of error that are not present in the MCNP-PoliMi models. Uncertainty in the detector positions, uncertainty in the neutron output of the APSTNG, and differences in detector efficiencies would contribute to the error. High background counts would also produce some error, although most of the background could be subtracted leaving only random fluctuations in the background level behind. In a physical measurement the configuration of the UO_3 powder in the reference measurement will most likely be unknown, so the coefficient *a* will have to be calculated by adjusting the value of the coefficient *a* using the total mass of the powder in the reference container and the relative densities at each pixel. Despite this, because of the accuracy with which the mass could be estimated using very short simulated measurement times, it is expected that a physical measurement could determine the UO_3 mass to within ±10% in a reasonable (< 1 hour) measurement time.

References

1. L. G. Chiang, A. C. Gehl, J. K. Mattingly, J. A. McEvers, J. T. Mihalczo, J. A. Mullens, R. B. Oberer, "Nuclear Materials Identification System Operations Manual," ORNL/TM-2001/65, Rev. 2, Oak Ridge National Laboratory, August 2001

2. T. Uckan, M. S. Wyatt, J. T. Mihalczo, T. E. Valentine, J. A. Mullens, T. F. Hannon, "Fissile Deposit Characterization at the Former Oak Ridge K-25 Gaseous Diffusion Plant by ^{252}Cf-Source-Driven Measurements," ORNL/TM-13642, Oak Ridge National Laboratory, May 1998

3. J.A. Mullens, P. Hausladen, P.R. Bingham, and J.T. Mihalczo, "Recent Imaging Measurements with NMIS at ORNL," *INMM Annual Meeting*, Phoenix, AZ USA, INMM, July 2005

4. J.T. Mihalczo, J.A. Mullens, J.K. Mattingly, T.E. Valentine, "Physical Description of Nuclear Materials Identification System (NMIS) Signatures." *Nuclear Instruments and Methods*, 450:531-555, August 2000

5. J.T. Mihalczo, P.E. Koehler, T.E. Valentine, L.D. Phillips, "Source Options for Nuclear Weapons Identification System," ORNL/TM-13025, Oak Ridge National Laboratory, July 1995

6. E. Padovani and S. A. Pozzi, "MCNP-PoliMi ver. 1.0 Users Manual", CESNEF-021125 Library of Nucl. Engr. Dept., Polytechnic of Milan, Italy, November 2002

7. M. Marseguerra, E. Padovani, S.A. Pozzi, "Simulating the Wrong Physics Can Generate the Correct Results," *3rd IMACS Seminar on Monte Carlo Methods*, Salzburg, Austria, September 2001

8. J.S. Neal, P.A. Hausladen, J.T. Mihalczo, "Alpha Particle Detector Development for a Portable Neutron Generator for the Nuclear Materials Identification System (NMIS)" *United Kingdom NMIS Training*, Oak Ridge, TN, USA, February 2007