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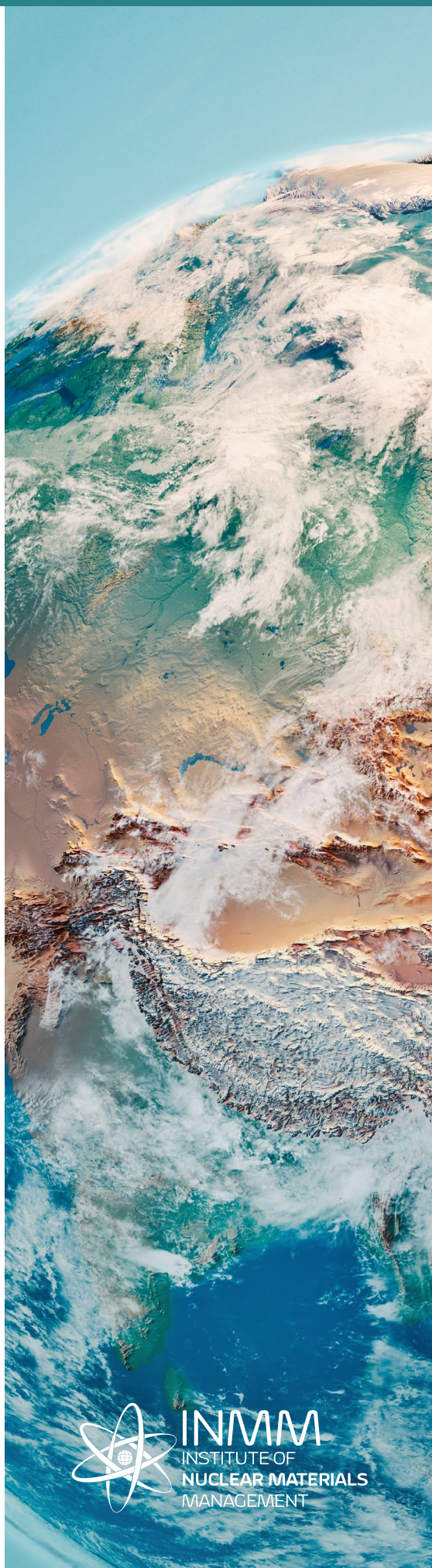

JNMM Journal of Nuclear Materials Management

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JNMM Journal of Nuclear Materials Management

Topical Papers

Institute News

Departments

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The Institute of Nuclear Materials Management is dedicated to the safe, secure and effective stewardship of nuclear materials and related technologies through the advancement of scientific knowledge, technical skills, policy dialogue, professional capabilities, and best practices.

INMM INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

President's Message

By Cary Crawford
INMM President

INMM Community,

Welcome to another edition of the JNMM. We hope you find the articles stimulating and valuable to your research and career interests. Since the last edition, the INMM held a strategic planning session in which the leadership discussed progress on our strategic planning efforts. Notable areas of progress include improvements to our website and methods of communication. We hope you've noticed some of these changes and agree they are for the better. Any suggestions you have are always welcomed.

We also spent a lot of time discussing our strategic partnerships with other professional organizations as well as our relationship with many government and nongovernmental organizations. We held meetings in conjunction with conferences at the IAEA and continue to work on our relationship with multiple international organizations in Vienna.

Most notably, the INMM Executive Committee decided to hold the 2021 Annual Meeting in Vienna to facilitate many of our non-US partners, chapters, and colleagues who might not otherwise be able to make it to the US for our Annual Meeting. While this obviously helps many of our members and chapters, it also creates a challenge for others and we ask that you understand our need to reach our broadest international audience and support our efforts as we open up avenues for their attendance. We are in the final stages of nailing down the exact dates and will get more information out as soon as we have it.

In the meantime, we continually seek to serve the needs of the Nuclear Materials Management community. The only way we can do this is if we hear from you and understand how we can better serve you. Please don't hesitate to reach out to any of our Executive Committee or Association Headquarters staff. We look forward to seeing you in July at our Annual Meeting in California!

Sincerely,
Cary Crawford
President, INMM

An Interesting Mix

By Markku Koskelo
JNMM Technical Editor

The JNMM editorial team has a number of contributed manuscripts in various stages of review. Three such contributed papers have made it through the process and are included in this issue. They present an interesting mix of topics.

The first one looks at the possibility of using building materials for nuclear forensics and safeguards purposes. Many building materials exhibit optically stimulated luminescence (OSL) characteristics. This allows them to potentially be used to measure whether nuclear material has been stored in a room well after the nuclear material has been removed.

The second paper is a student paper which explores the present state of the security of radiological sources in Russia. Russia is one of the largest producers and users of radiological sources for peaceful purposes. While the security of special nuclear materials is of great concern, the paper makes a claim, and correctly so, that the security of these other types of radiological sources should not be overlooked.

The third paper discusses the testing for corrosion of the widely used SAVY containers that are used for long term storage of nuclear materials. There is an increasing need to store nuclear materials somewhere, and doing it safely and securely is of great importance.

In his column, "Taking the Long View in a Time of Great Uncertainty", Jack Jekowski, Industry News Editor and chair of the INMM Strategic Planning Committee, gives us a wonderful review of how the INMM leadership is listening to its membership and advancing the INMM's mission in the midst of global turmoil.

Should you have any comments or questions, feel free to contact me.

Markku Koskelo
JNMM Technical Editor

There is an increasing need to store nuclear materials somewhere, and doing it safely and securely is of great importance.

Potential Retrospective Uranium Enrichment Determination Using Solid State Dosimetry Techniques on Ubiquitous Building Materials

Robert Bruce Hayes,
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Abstract

Recent research has shown how nuclear materials can be imaged and characterized retrospectively using thermoluminescence, optically stimulated luminescence,[1] and/or electron paramagnetic resonance of insulating materials such as quartz in brick or other ceramics. The technology effectively places a gamma camera in every kitchen (based on an array of ceramic coffee cups). It similarly places a low-resolution gamma spectrometer in every bathroom (requiring measuring dose depth profiles into porcelain fixtures). Large regional arrays exist in the form of telephone pole insulators, and the list could just keep growing from there. What this work specifically focuses on is the potential to carry out retrospective assay of UF_6 regarding historical enrichment levels. With proof of retrospective assay and characterization now being demonstrated, this important question as to whether we can reconstruct historical uranium enrichment levels at a nuclear facility becomes viable. As a proof of concept, this paper reviews the technology and the theory that would allow for such a measurement capability in cases where UF_6 canisters have been used only once and have been allowed to sit unmolested for many months.

Introduction

Radiation dose measurements can constitute a technically difficult endeavor due to a rich assortment of physics that take place when one performs imaging and characterization of nuclear material. Electronic equilibrium,[2] attenuation factors, and spatial distributions all contribute to the effects to be considered and addressed. This has already been accomplished in modern personnel dosimetry, in which thermoluminescent dosimeters (TLDs) and optically stimulated luminescence dosimeters (OSLDs) are commonly used for measuring a worker's dose. Another means for dose measurement is that of electron paramagnetic resonance (EPR), which is a method recommended by the National Institute of Standards and Technology for secondary standard dose rate calibration.[3] Technically, each of these methods offers various ways to measure historical doses, which can also be referred to as *retrospective dosimetry*.[4] Now that empirical proof-of-concept measurements have been obtained,[1] the initial theory laid out for this approach[5] warrants reconsideration, as given here.

Retrospective Dosimetry

The method provides only dose measurements, and so activity estimates would have to be based on knowledge of possible dwell times for the nuclear materials. This could be as long as the facility itself or could be based on other intelligence, such as how long a facility rejected International Atomic Energy Agency inspections. In any case, this gives a maximum dwell time, and knowing the dose, this gives a minimum dose rate to which a minimum activity can be ascribed.

As with any radiation detector, this technology is subject to background effects. Basically, in order to have a high signal-to-noise ratio, the dose of interest has to be large compared to the integrated background to the dosimeter of interest. In general, anthropogenic nuclear materials already satisfy this by many orders of magnitude, but this requires obtaining your dosimetric material reasonably close to the historical locations of nuclear material being characterized retrospectively.

Again, as with any radiation detector selection, different detectors have different pros and cons. Some are more sensitive than others, and some have higher noise or lower resolution. Thermoluminescent (TL), optically stimulated luminescence (OSL), and EPR dosimetry basically fall into the low-resolution category but mitigate this by being ubiquitous. They also do not enjoy having all materials of use being highly sensitive (such as cellulosics or some organic synthetics that also can have short half-lives), but many materials of use have stability measured in millions of years, such as quartz and bone.

Retrospective Characterization

Taking as an example a slab layer of bricks that are sampled and sectioned to obtain dose depth profiles over a grid, additional details should be considered. The geometry is provided in Figure 1, where a gridded cross shows sampling locations. Equation 1

provides the shielding dependence on source position in polar coordinates. If any of the measurement locations were sampled as a core that could be sliced for dose depth profiling, this depth dependency as a function of the source location and total fluence is given in Equation 1. Equation 2 gives the positional dependency along the grid of surface measurements.

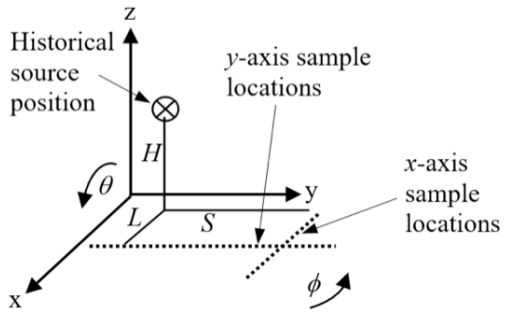

Figure 1. Coordinate definitions for dosimetric dependence on sample positions and depth for retrospective imaging and assay measurements

$$A(r) = I_0 \cdot e^{-(H/\sin\theta)\cdot\mu_{en}} \quad (1)$$

$$A(H, L, \theta, \emptyset) = I_0 \cdot [(H/\cos\theta)^2 + (L/\sin\emptyset)^2]^{-1} \quad (2)$$

Here, I_0 includes units and conversion factors for the dosimetric unit of choice. m_{en} is the mass energy absorption coefficient. Bear in mind that Equations 1 and 2 represent point samples and that sample sizes should be negligible compared to the scale of the system. Similarly, obtaining electronic equilibrium and avoiding inhomogeneities are not included in this analysis, nor is source motion. If, however, the source were spent fuel being moved through an area, it would simply appear as an extended source having continuous spatial distribution along the transport path, assuming a constant speed. The point source effects required for using Equations 1 and 2 without modification are not in general expected to be valid, and so the method proposed in this work would often require integrating dose deposition effects from all source materials combined.

The approach then requires that a sufficient gridded sample array is obtained on orthogonal axes to sufficiently reconstruct all historical sample configurations. Rather than using Equation 2, a point kernel approach might be taken, or a simple library of credible source deposition profiles could be used as a fitting function to any empirical measured distribution. These would be the resultant superposition of all gamma energies at the known branching ratio for a given isotope of interest, because the empirical result would not be a single attenuating exponential profile but a more complicated profile that could be discriminated more readily if libraries of these were to be generated. Once the source distributions are known, the relative contributions from all radiation types can then be calculated as a function of depth at any core location and can be compared to measurement for an enrichment determination.

Typical detection limits in ubiquitous materials range from hundreds of μGy up to tens of mGy, depending on the material in question, but recent research[6] has shown that the energy resolution (required for estimating m_{en}) is approximately 10% for ^{241}Am, placing the ability to do this kind of analysis well within reach.

Typical TL and OSL elements used in personnel dosimetry include lithium fluoride and aluminum oxide. In addition to these materials, quartz, feldspar, sodium chloride, and a large list of other ubiquitous materials can be used as good TL, OSL, or EPR dosimetric material.[4] To the extent that these materials could also be sampled and divided into slices, dose depth profiles can be measured and used to determine gamma energy distributions and discriminate particle types (α, β, neutron) when the samples have measured density and known chemical compositions. Figure 2 shows an example of recent measurements from retrospective measurements using OSL in brick from ^{137}Cs and ^{60}Co, comparing the reconstructed doses to the MNCP® calculated values. Clearly, there is some bias in the results that should be removed with proper calibrations, but the correlation is unmistakable. In principle, with nothing else changed, the only error that would be introduced by not correcting for this effect is the total dose given by the sources. Typical dose rates from a UF_6 cylinder are 0.8 mGy hr^{-1}, so these doses would require exposure times on the order of many months.[7]

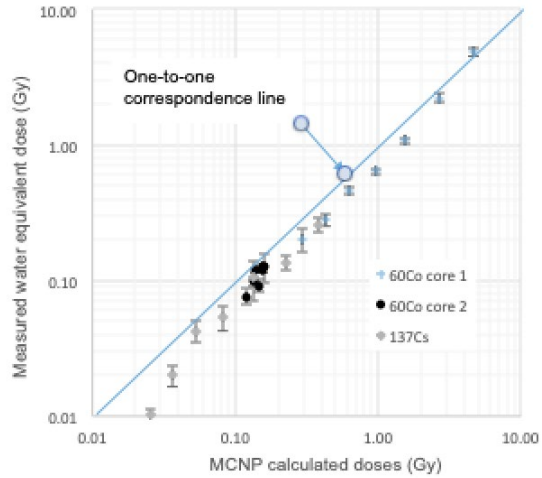

Figure 2. Measured doses shown as a function of expected doses based on Monte Carlo N-Particle Transport Code (MCNP) calculations. Values are obtained for different slices taken from separate cores, making three dose depth profiles[1]

Enriched Uranium

When enriching uranium, the decay product of ^{234}U also gets enriched relative to natural abundance along with the ^{235}U. The values assumed for isotopic abundances of 90% enriched and 5% enriched uranium (highly enriched uranium [HEU] and low enriched uranium [LEU], respectively) were taken from the literature[8] to generate time-dependent radiation profiles for each material.

Results and Discussion

To calculate such things as dose deposition into an external TLD or OSLD material, such details would have to include the composition of the source material, any interstitial material between the source and dosimetric material, and the configuration of the dosimetric material itself. The source configuration assumed is a 30B container[9] filled with UF_6 surrounded by a brick box that is 7 cm thick.

Retrospective Imaging and Energy Discrimination

Spectral discrimination is the key to enabling isotopic determinations. The technical basis for being able to characterize any gamma source in terms of its energy is shown schematically in Figure 3 as the calculated mass energy absorption coefficient (m_{en}/ρ). The value of m_{en}/ρ is calculated as a superposition of the standard chemical components[10] and the elemental values[11,12] for m_{en}/ρ. The difference between the 186 KeV peak from ^{235}U and the 1 MeV peak of ^{234m}Pa has a similar value for m_{en}/ρ, which would be a component of difficulty using this specific material for discriminating those two energies. As in all scenarios for luminescence dosimetry for historical source characterization, the total series of contributions to the luminescence signal must be considered, including the decay gamma, neutron-induced, and Bremsstrahlung components.

The main contributions to an external dose for an OSL or TL dosimetric material from UF_6 include the following: (1) ^{234m}Pa gamma emission, (2) Bremsstrahlung from ^{234m}Pa beta, and (3) gammas generated from alpha-n scatters and absorptions, but also to a lesser extent from spontaneous fission (the latter primarily from ^{238}U) and the 186 keV peak from ^{235}U. Additional contributions include the entire decay series set of gammas, which grow into a freshly generated UF_6 container. All of these components were modeled and simulated using the MCNP6[13] and SCALE[14] tools. The relative contributions from each of these depend on the enrichment and, for some components, the time since creation.

Uranium Hexafluoride

Figure 4 shows the neutron spectrum from both alpha-n reactions as well as spontaneous fission for both HEU and LEU, as calculated by the Oak Ridge Isotope Generation and depletion (ORIGEN) code. The HEU has the larger alpha-n component due to the larger specific activity of the uranium arising from the shorter half-life of ^{235}U. Similarly, the spontaneous fission portion is larger in the LEU due to the larger fraction of spontaneous fissions which occur in ^{238}U. In both cases, the spectrum is dominated by the alpha-n portion of the distribution.

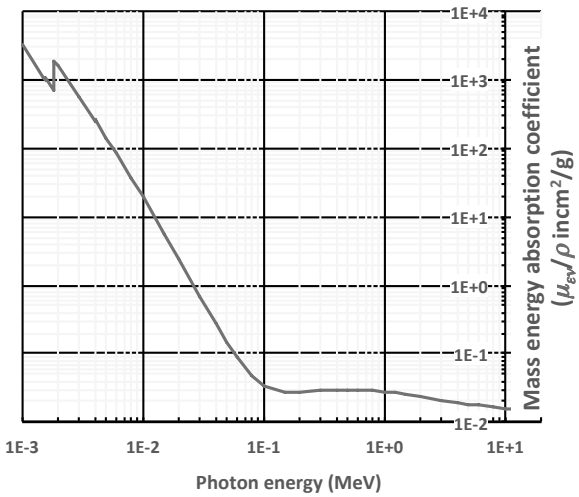

Figure 3. Mass energy absorption coefficient for a standard silica brick

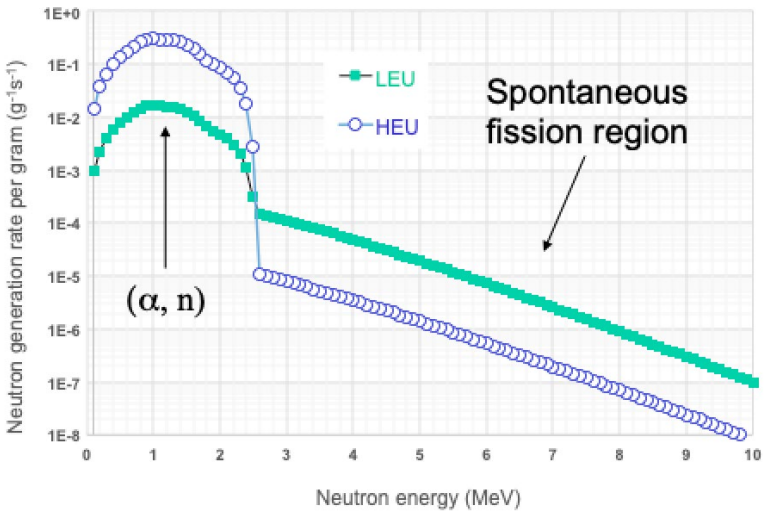

Figure 4. Neutron energy distribution displaying the alpha-n and spontaneous fission regions for both highly enriched uranium (HEU) and low enriched uranium (LEU)

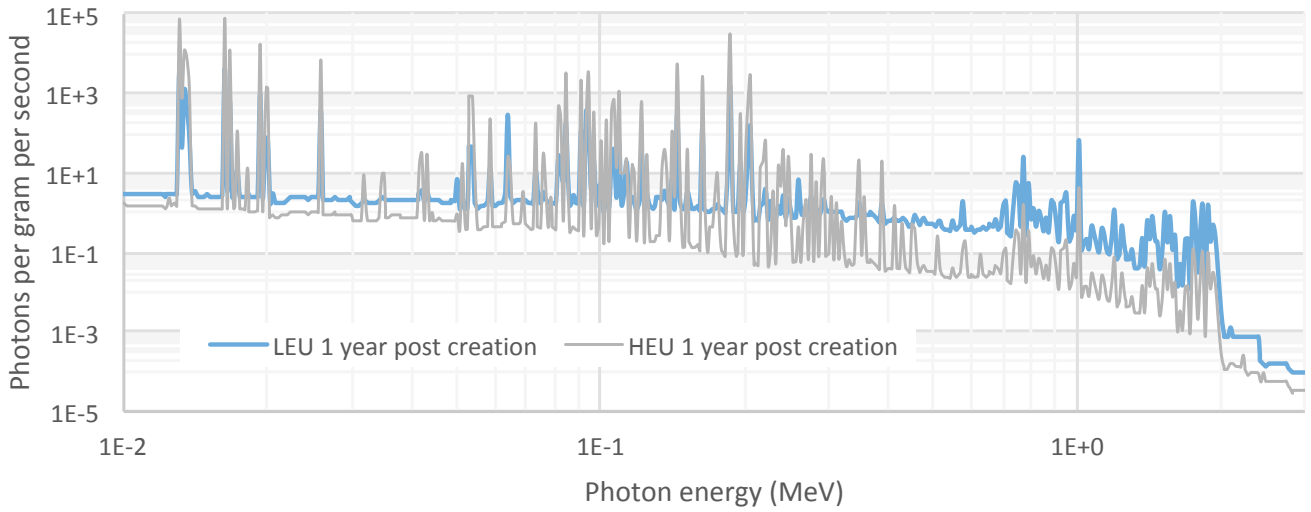

Figure 5. Gamma spectrum generated after 1 year of decay product ingrowth for LEU and HEU. This would be generated uniformly within the UF_6 material

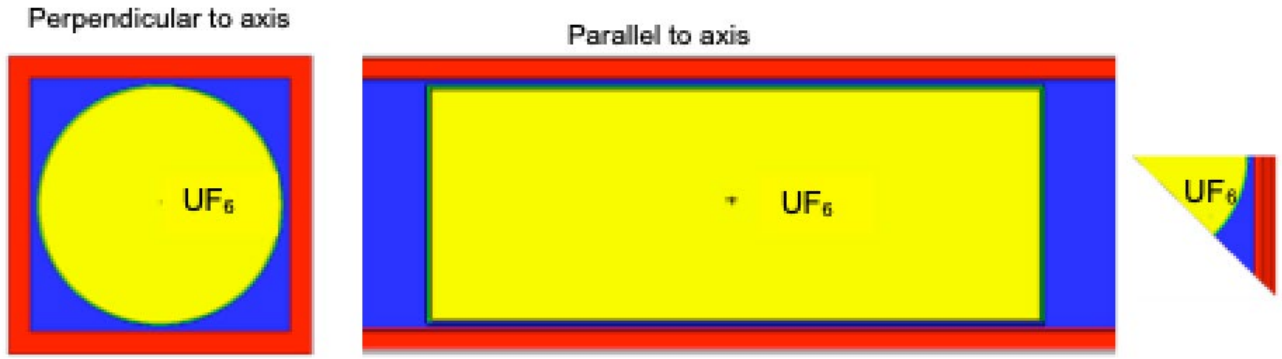

Figure 6. Equivalent geometry utilized to calculate dose deposition tallies in brick material originating from a 30B canister filled with UF_6. The inset on the far right shows the actual sections with reflecting boundaries above and to the lower left with the canister also cut in half (and reflected) along its axis

The resulting gamma spectrum from both HEU and LEU neutron sources is largely indistinguishable, which is attributed to the dominant component of each neutron spectrum being that from the uranium decay alpha particle impacting the fluorine nucleus, releasing a neutron in the process. Similarly, the spectrum from the Bremsstrahlung of the ^{234m}Pa beta would be identical in shape but not in magnitude, being much larger in LEU than HEU. Figure 5 shows the decay product gamma emissions from LEU and HEU as calculated by ORIGEN.

MCNP Configuration

As a means of simplifying the geometry and to accomplish variance reduction, a symmetric system was assumed for the brick dose deposition profiles. The dose to layers is calculated for the entire planar layer of each specified thickness, and the 30B canister is contained in a brick box into which the dose deposition is calculated. As such, the symmetry allows halving and quartering of the system, which enables reflecting boundaries to enclose the system. Through weight-biasing particles toward the tally surface shown in Figure 6, this effectively gives a fair variance reduction scheme to push particles out of the canister for tally calculations.

The central cylinder approximates a completely full 30B UF_6 canister. The outer parallel-piped shell is modeled as silica brick with the interstitial material between the canister and the brick being dry air. The dose deposition was calculated only to the layer of brick parallel to the cylinder axis.

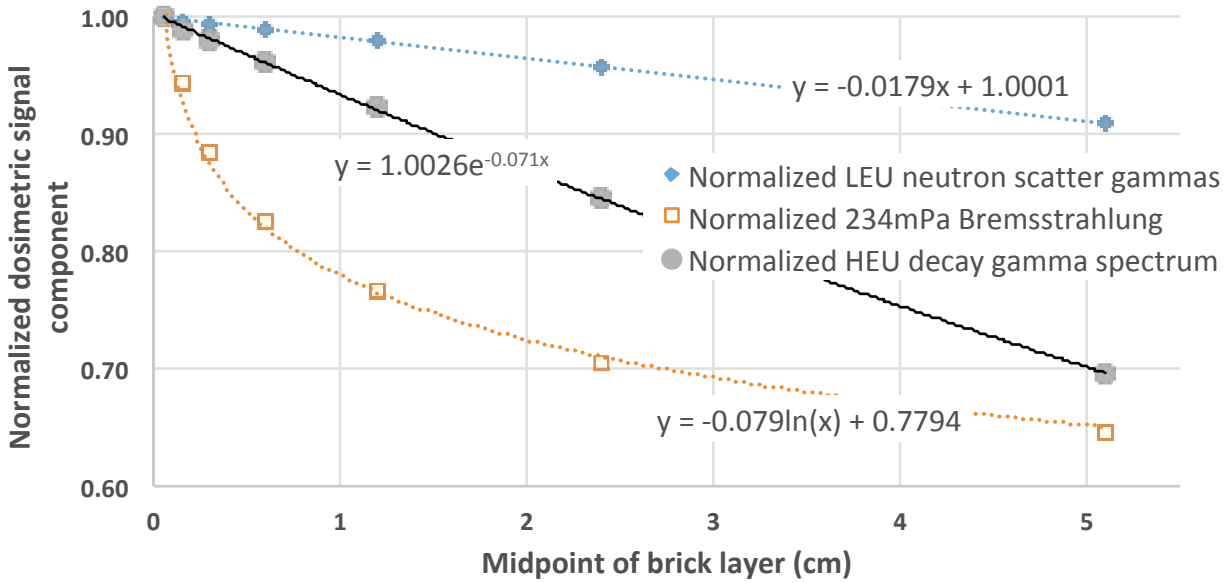

Figure 7. Attenuation description for dose in a material as a function of the material's thickness. The functional form and parameters of the fits are entirely arbitrary and only intended to demonstrate clear distinctions in attenuation profiles from different source terms

Dose Deposition Profiles

The key element in obtaining energy distribution information is the differential attenuation effects of the dose profiles into the material. Dose profiles over a grid primarily give source location information, but to start estimating source isotopics, energy discrimination must be obtained. The gamma distribution originating in the UF_6 is not the incident field on the dosimetric material, but rather the spectrum after self-attenuation and penetrating the shielding of the 30B container. Of seminal significance to this technique is their resultant dose deposition profiles into external dosimetric materials (which here are simulated as a brick layer sampled from a single brick slab).

These spectral distributions from either the ^{234m}Pa beta Bremsstrahlung or the neutron-generated gamma would not necessarily be expected to give a single exponential distribution into a material. This is shown in Figure 7, where the Bremsstrahlung from the ^{234m}Pa is showing the effects of its lower energy regions being attenuated out much faster than its higher-energy portions, with the neutron-induced component appearing approximately linear over this material's range. The values are all normalized to have unity amplitude at the origin to show them on the same scale. The key element to note is that the contributions from each component are a function of enrichment, so deconvoluting the various contributions would provide measurement evidence of historical enrichment values.

This does not address the potential for multiple enrichment values in an array, nor does it address the potential for canisters to be dynamic such that they are randomly replaced by newer, older, or even depleted uranium UF_6 canisters. In a realistic scenario, the use of Equations 1 and 2 are almost entirely invalid as they assume only simplistic plane wave and point source effects are taking place. It is simply assumed here that typical nuclear facility operations would be undertaken such that consistency can be reliably expected, but this is certainly not guaranteed in general. If this is not the case, the evidence would demonstrate such, although this alternate finding may be of use in and of itself for safeguards applications.

Deconvoluting the enrichment

By measuring the dose deposition in brick and determining the relative contribution from each of the terms seen in Figure 7, one should be able to retrospectively determine uranium enrichment using dose reconstruction techniques. It cannot be said what minimum difference in enrichment can be detected at this point because there are no proof-of-concept measurements to evaluate, just these MCNP and SCALE simulations. Typical detection limits for luminescence techniques are in the tens of mGy, and with UF_6 canisters generally producing dose rates[6] around 0.08 mGy/hr, storage for any length of time beyond a few weeks should be detectable (for example, see Figure 2). Note that detection limits

here are simply based on signal to noise present at integrated doses comparable to background.

The overall trend would be that as enrichment increases, neutron components increase and Bremsstrahlung components decrease. This would all be superimposed on the decay series gamma distribution shown in Figure 5. The details of the response profiles will depend on the sampling protocols as shown in Figure 1, which will have certain differences to the averaged sampling distribution modeled here, as shown in Figure 6.

Uncertainty contributions

The errors associated with calibration are overall negligible compared to those that might occur due to uncharacterized effects in the dose deposition profiles. This includes the effects from heels — when canisters are reused and the uranium decay products remain in the canister after it is emptied. Until analysis has been done to characterize the potential contributing effect expected from that source term, it is difficult to predict the magnitude of this effect on the potential quality attainable from this approach. What also has not been analyzed is the potential effect from using only fresh or very aged UF_6, as this might be an important bias. The theory presented here does not require a good estimate of the total dose (which scales with the source's dwell time), but this may be an important factor when the contribution from heels is taken into account. In fact, if any canister is not placed long enough for its integrated dose into the surroundings to be large compared to background (many weeks at least), the background itself can become a large uncertainty contribution. Any additional source terms, such as contamination, might also play a role in the uncertainty to the extent that it is present.

Smaller uncertainties include multiple sample preparation effects, statistical fitting of spatial distributions on the gridded array, and dose depth profiles. The background dose rate could be fitted as an asymptotically approached constant if it is not negligible, or it could be measured in situ with OSLDs or TLDs. It is hoped that future analysis will further illuminate the corrective actions that may be necessary to address these potential liabilities in the method.

Limitations and Considerations

Most gamma ray spectrometers allow multiple spectra over short intervals of time. The proposed technology effectively produces a single gamma spectrum over its lifetime. Similarly, background contributions slowly increase over time such that the detection limits will also slowly increase in relation to the ambient background, which can include internal, cosmic, and terrestrial sources. The use of a grid sampling distribution to conduct imaging (via inverse square spatial profiles) may allow 3-D reconstruction of point sources, but again gives only a long time integration. In this way, source characterization depends on fixed configurations just as it does with portable detectors, but with such long integration times, fixed source to detector geometries may prove elusive in many cases.

Furthermore, this approach requires destructively sampling facility structures such that a core must be removed to acquire this information — which is not likely to be volunteered from an operational facility. If staging materials such as placer bricks or ceramics were in the environment, these could certainly serve in this capacity if they were known to have been placed in a fixed configuration during exposure. Some materials may also have sample preparation requirements that are unique if previously characterized impurity and additives are not present. Finally, the method offers only low-resolution energy discrimination, which ends up being a function of the mass energy absorption coefficient of the particular material being used for the dose reconstruction, which depends on the elemental distribution of the ceramic detector material.

Conclusions

The relative strength of any particular profile will actually depend on the age, storage time, and enrichment. Multiple other factors, such as the use of reprocessed uranium or any other input (such as down-blended uranium), have not been considered. Likewise, actual dose deposition profiles are not considered for a single spot core-type measurement but just averages over a spatial distribution where full 30B canisters are stored in a planar array. This analysis accounted for the total distribution and self-attenuation of the UF_6 but did not simulate any of the heels that can build up in a reused canister. The analysis considered only a single enrichment in fixed configurations, and true operational situations would understandably be more complex.

Likewise, the potential caveats present with any traditional detector media are all present with the proposed approach. These include background contributions, mixed sources and distributions, energy resolution, time integration, and internal radioactivity. The proposed method suffers from substantially lower performance than traditional detector platforms but does enjoy the benefit of being freely predeployed in every nook and cranny where nuclear operations have been, are being, and will be conducted. As such, it offers a new capability to consider in

the nuclear forensics toolkit.

Substantially more work is required to fully realize the detailed retrospective assay of uranium by dosimetric measurement of fired materials, including sample acquisition, preparation, and even measurement and analysis. This work shows that the theoretical and analytical capabilities are sufficient to realize this potential and shows definitive promise in providing a powerful forensic tool for evaluation.

Keywords

Uranium, retrospective dosimetry

Acknowledgments

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Appendix 1: HEU Gamma and Neutron Spectrum Example from SCALE

```
=origen
bounds{
neutron = [499L 5e7 0.00005] %neutron="xn28g19v7.1"
gamma = [9999L 10e6 50] %gamma="xn28g19v7.1"
% insert bounds components here

}

case{
% use ENDF/VII-based decay library
lib{ file="end7dec" }
% create a material with 1 gram U-238
mat{
units=grams %gives emission per gram
iso=[u238=2.2584e2 u235=1.1892e1 u234=0.11118 f=54]
}
time{
units=years
t=[3L 0.001 100]
}
neutron {medium=2}
gamma {continuum=yes}
print{
nuc{ units=[moles curies] } %Ci/g
ele{ units=[moles curies] } %Ci/g
neutron{
sources=yes
spectra=yes
detailed=yes
}
gamma{
spectra=yes
}
}
save{ file="LEU.f71"
steps=[3i 0 4 ]
%or steps=[21L 0 22] % use linear interpolation
}
}
end

=opus
data="LEU.f71"
typarams=ansp
npos=5 end
end
=opus
data="LEU.f71"
typarams=nspe
npos=5 end
end
=opus
data="LEU.f71"
typarams=gspe
npos=5 end
end
%
% iso=[u238=0.949543 u235=0.05 u234=0.000467 f=6]
%
%= Nuclide concentrations in gram-atoms for case '1' (#1/1) =
%-----------------------------------------------------------------------------------------------------------------
% (relative cutoff; integral of concentrations over time > 1.00E-06 % of integral of all concentrations over time)
%.
% 0.0E+00y 1.0E-03y 3.0E-03y 1.0E-02y 3.0E-02y 1.0E+00y 3.0E+00y 1.0E+01y 1.0E+02y
% f-19 3.1582E-01 3.1582E-01 3.1582E-01 3.1582E-01 3.1582E-01 3.1582E-01 3.1582E-01 3.1582E-01 3.1582E-01
% u-234 1.9954E-06 1.9954E-06 1.9954E-06 1.9954E-06 1.9954E-06 1.9954E-06 1.9954E-06 1.9953E-06 1.9949E-06
% u-235 2.1273E-04 2.1273E-04 2.1273E-04 2.1273E-04 2.1273E-04 2.1273E-04 2.1273E-04 2.1273E-04 2.1273E-04
% u-238 3.9888E-03 3.9888E-03 3.9888E-03 3.9888E-03 3.9888E-03 3.9888E-03 3.9888E-03 3.9888E-03 3.9888E-03
```

Appendix 2: Bremsstrahlung Dose Deposition in Monte Carlo N-Particle Transport Code (MCNP)

```
MCNPX Visual Editor Version X_24E
c  LEU 1yr old
  1    0        15 :24 :-25 :-23 :26  $outside universe
  4    4 -0.001205 (-24 1 -16 25 -26 23 ): $air surrounding cylinder
       (-1 -26 4 -24 25 )
  6    2  -4.68 -24 25 -2 23 -5  $HF6
  7    1  -7.874 (23 -5 2 -1 -24 25 ):(-1 -4 5 -24 25 ) $canister
  8    3   -1.8 -24 25 16 -17 -26 23
  9    3   -1.8 -26 23 25 -24 17 -18
 10    3   -1.8 -26 23 25 -24 18 -19
 11    3   -1.8 -26 23 -24 25 19 -20
 12    3   -1.8 -26 23 -24 25 20 -21
 13    3   -1.8 -26 23 -24 25 21 -22
 14    3   -1.8 -26 23 22 -15 -24 25

  1      cx 38.1
  2      cx 36.83
  4      px 96.52
  5      px 95.72625
 15      py 47
 16      py 40
 17      py 41
 18      py 42
 19      py 43
 20      py 44
 21      py 45
 22      py 46
*23      px 0
*24      pz 0
*25      p 0 1 1 0
*26      px 120

mode  p e
m4   6000.       -0.000124  $air
     7000.       -0.755268 8000.       -0.231781 18000.       -0.012827
m1   6000.          -0.002  $ HT9 stainless as ASTM A516
     14000.         -0.004 15000.         -0.0003 16000.         -0.0002
     23000.         -0.003 24000.         -0.115 25000.          -0.006
     26000.         -0.8495 28000.          -0.005 42000.          -0.01
     74000.         -0.005
m2   9000.              6  $HF6
     92000.             1
m3   8000.          -0.525  $brick
     13000.         -0.005 14000.         -0.449 20000.          -0.014
     26000.         -0.007
imp:p   0          1 9r         $ 1, 14
imp:e   0          1 9r         $ 1, 14
vol   0 4r       4980       5100       5220       5340       $ 1, 12
      5460       5580        $ 13, 14
sdef  par=e  POS=0 19 -8 RAD=d3 EXT=D1 AXS=1 0 0  erg=d2   ccc=6
phys:p
phys:e
si1   0 95.72625
sp1   -21 0
si3   0 20.5
sp3   -21 1
c     Pa234m from Health Phys. 83(4):471-475, 2002
si2 L  5.70E-02   1.71E-01   2.85E-01   3.99E-01   5.13E-01
       6.27e-01   7.41E-01   8.55E-01   9.69E-01   1.08E+00
       1.20e+00   1.31E+00   1.43E+00   1.54E+00   1.65E+00
       1.77e+00   1.88E+00   2.00E+00   2.11E+00   2.22E+00
sp2 D  5.63E-02   6.52E-02   7.22E-02   7.73E-02   8.04E-02
       8.14e-02   8.05E-02   7.77E-02   7.33E-02   6.76E-02
       6.07e-02   5.31E-02   4.49E-02   3.64E-02   2.81E-02
       2.01e-02   1.30E-02   7.10E-03   2.79E-03   4.27E-04
f2:p  16
ft2   GEB 0.00116 9.02e-7 3.97e5
f18:p 7
ft18 GEB 0.00116 9.02e-7 3.97e5
f28:p 4
ft28 GEB 0.00116 9.02e-7 3.97e5
e2    0  0.01 2047i 10
e18   0  0.01 2047i 10
e28   0  0.01 2047i 10
ctme 1000
```

Re-examining the State of Radiological Source Security in Russia

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Abstract

Securing radioactive sources presents a unique and complex challenge due in large part to their diverse physical properties, applications, and operating environments. Considerably more prevalent than nuclear materials, radioactive sources are used throughout the world for medical, industrial, agricultural, research, and other purposes. Sources can be found both at hospitals in city centers, through which thousands of people pass daily, and at highly remote locations, where individuals or small teams use portable devices for a variety of industrial purposes. Over the past 75 years, Russia and the former Soviet Union have produced at least half a million of these individual ionizing radiation sources for domestic use, and since the fall of the Soviet Union, Russia has continued to serve as one of the world's largest producers, users, and exporters of long-lived radiological sources. Although perhaps the ultimate security threat facing the world today is a terrorist organization procuring fissile nuclear materials for use in an improvised nuclear device, it is far more likely that terrorist organizations would manage to obtain radiological materials for use in a dirty bomb, which can have significant effects if used in areas of high population density.

Introduction

Securing radioactive sources presents a unique and complex challenge due in large part to their diverse physical properties, applications, and operating environments. Considerably more prevalent than nuclear materials, radioactive sources are used throughout the world for medical, industrial, agricultural, research, and other purposes. Sources include radioactive materials that are encapsulated in solid form and can range from iodine seeds used for internal radiotherapy treatment, to industrial irradiators weighing several tons, used for large-scale sterilization at fixed facilities. Sources can be found at both hospitals in city centers, through which thousands of people pass daily, and highly remote locations, where individuals or small teams use portable devices for a variety of industrial purposes. Many facilities that use these radiological sources in various applications are not well-protected — they are open facilities with minimal or no physical protection or trained on-site security forces. These are, by their very nature, open environments and are accessible for large numbers of people. Poor chain-of-custody procedures and insufficient regulatory controls have led to loss of control over thousands of radioactive sources. Even in States with regulatory controls in place, high disposal costs and a lack of repositories have led end users to abandon radioactive sources at the end of their life cycle.

These challenges are only magnified in Russia, as the size and complexity of Russia's life-cycle management of radiological sources presents a major challenge both for Russia's domestic policy and for the international community. Over the past 75 years, Russia and the former Soviet Union have produced at least half a million individual ionizing radiation sources (IRSs) for domestic use. Russia has long been one of the world's largest producers, users, and exporters of long-lived radiological sources — it is the only producer of caesium-137 (Cs-137) for worldwide distribution and produces roughly one-half of the world's cobalt-60 (Co-60). These are also the materials that could be used to build a radiological dispersion device (RDD), more commonly known as a dirty bomb. Since the fall of the Soviet Union, challenges have persisted with securing these radiological sources. Due to neglect, loss, and inadequate security, some of these radioactive sources are in unknown locations or states of use. Consequently, serious risk exists of these materials falling into the wrong hands. Indeed, facing severe budgetary constraints due to its weakened economy, the Russian government is unlikely to prioritize funding for security of these sources, let alone develop a comprehensive inventory of all sources located inside the country.

This paper will present an overview of the state of radiological source security in Russia today, highlight progress made to date to improve Russian radiological security, and raise questions relevant for both Russian and international security. It is important

to note at the outset, however, that this overview is hindered by the lack of publicly available information on this issue.

Russian Materials and Facilities

According to a 2007 report by the National Academy of Sciences, Russia (and the former Soviet Union) produced at least 500,000 radioactive sources over the past 75 years.[1] Some estimates put the figure at close to a million sources, although the total figure is unknown due to poor accounting of these sources during and after production. Russia is also one of world's largest producers and exporters of many of these materials, which include Cobalt-60 and Caesium-137, both highly radiotoxic IAEA Category 1 sources.[2] These radiological sources are used in various processes and pieces of equipment and can be found throughout the country in a variety of facilities.

Materials: Radioisotope Thermoelectric Generators

A major source of concern for radiological security in Russia are radioisotope thermoelectric generators (RTGs). Invented in 1954, RTGs were created as a desirable power source for equipment and installations without regular human interaction. RTGs could provide steady amounts of power over a much longer period of time than fuel cells, batteries, or other types of generators.[3] From the 1970s to 1990s, the Soviet Union built over 1,000 RTGs for use in installations such as unmanned lighthouses and navigation beacons. These RTGs, powered by strontium-90 (Sr-90), were given a life span of 10 years. All of these RTGs far outlived their expiration dates and were left to decay throughout Russia. Some of them were stripped of their casings, not only exposing the core to nature, but also endangering people that came into contact with the irradiated metal.[4] The process of locating and decommissioning these RTGs began in 2001, when Norway initiated international cooperation. Within the next several years, the United States, Canada, and France joined the process. As of September 2016, the international coalition has located and decommissioned all but 13 RTGs throughout Russia and the Arctic Circle. The United States has helped locate and decommission 487 of these recovered RTGs, totaling over 30 million curies of radiological material secured, making it the leading partner in this coalition.[4]

Many of these RTGs have been replaced with alternative power sources (APS units). These APS units run on solar power in all but a few special cases, in which the French built hybrid solar- and wind-powered APS units. Replacing RTGs with APS units presents a challenge in many cases, not only because of the different environments these APS units need to be constructed for, but because removing RTGs can be an arduous process.[5]

Materials: Other Ionizing Radiation Sources

In 2007, the Committee on Opportunities for U.S.–Russian Collaboration in Combating Radiological Terrorism released a comprehensive report detailing collaboration between the two nations. The committee worked with the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE) to prepare a report on the distribution, protection, and control of IRSs in Russia. IBRAE reported to the committee that more than 500,000 IRSs were in Russian possession, although outside experts believe that the number is far larger than that, possibly reaching close to 1 million. In addition, Russia has been one of the world's leading exporters of radionuclides and IRSs for many years.[1]

These IRSs, both Soviet and Russian made, are located throughout Russia and the former Soviet territories in varying states of use and security. According to a 2014 report issued by the National Nuclear Security Administration (NNSA), Russia currently has over 800 buildings with high-activity sources in use. These buildings include everything from medical facilities to industrial sites. In an effort to effectively mitigate the threat of radiological material theft, the NNSA's Global Threat Reduction Initiative (GTRI) program has worked with these sites to design, install, and maintain upgrades as well as supplement physical protection upgrades with comprehensive training on radiological security principals and incident response. As of November 2014, the GTRI program has worked to upgrade the physical protection of 295 of these buildings.[6]

In accordance with provisions in the International Atomic Energy Agency (IAEA) Code of Conduct on the Safety and Security of Radioactive Sources, which Russia has made a political commitment to support, the regulatory authority should have in place the means to ensure that sealed radioactive sources are kept under constant control by authorized users and that any orphan sources discovered within their territory are promptly brought under regulatory control and managed safely and securely. However, due to funding limitations, insufficient staffing and training, inadequate equipment, and the lax enforcement of laws and regulations, Russia continues to face challenges with orphan sources.[7]

Many of these materials may not have been subject to regulation, or they may have been regulated initially but then abandoned, lost, misplaced, stolen, or removed without authorization. These end-of-life and orphaned sources present their

own unique security vulnerabilities. Orphan sources by definition have no one purposefully providing security. The acquisition of an orphan source for malicious purposes would go unnoticed and unreported.

Although it is unknown exactly how many radioactive sources have been orphaned over the decades, as of November 2014, the GTRI program has helped locate and recover over 10,000 disused or orphaned sources throughout the former Soviet Union, totaling nearly 1 million curies.[6]

Waste Management Facilities

Radon facilities were established beginning in the 1960s as a means of collecting, transporting, processing, and disposing of low- and intermediate-level radioactive waste (LILW) and disused sealed radioactive sources (DSRSs). Thirty-five Radon facilities were built in the former Soviet Union, with 16 of them now residing within Russian Federation territory.[8]

DSRS containers contain radioactive waste with high levels of specific activity. The average radionuclide composition within these DSRS containers is 40% Cs-137, 25% Co-60, 22% Sr-90, 8% iridium-192 (Ir-192), 4% thulium-170 (Tm-170), and 1% plutonium-239 (Pu-239). As of 2006, all of these sites had nearly met their maximum capacities for radioactive waste storage, and Russia has struggled to identify and fund a permanent repository for the disposal of radioactive waste.[8] Russia has not agreed to recycle or repatriate sources created prior to 1992, which has significant repercussions for other nation-states because Russia is a major manufacturer and exporter of several key isotopes (such as americium-241 [Am-241] and Cs-137) that are actively used in equipment around the world.

Several Radon facilities are operated as disposal facilities for institutional LILW without intention of waste retrieval. The radioactive sources are placed within large metal drums that are then filled to capacity with concrete. The containers are then buried several meters below the ground. Radioactive sources with very high levels of specific activity are sometimes given twice the protection — placed in a small drum filled with concrete, which is then placed in a second, larger, drum that is also filled with concrete.[8]

While the 16 Radon facilities continue to serve as regional storage and disposal facilities that handle a wide variety of unwanted and spent IRSs, many have already reached their maximum storage capacity. This will continue to present Russia with waste management challenges until the necessary political, financial, and legal obstacles are cleared and a designated national waste repository is identified.

Security Concerns

Throughout these radiological facilities, as well as government accountability offices, security issues have presented themselves in several different ways. The following section addresses these security issues.

The central component of control and accounting of IRSs is the network of information and analytic centers (IACs) supporting the various ministries, agencies, and other federal-level organizations involved with nuclear and radiological security in Russia. Issues with the network of IACs lead to issues with the security and assessment of IRSs. Several common issues have been reported in regard to IAC operations, and almost all of them can be linked to insufficient funds.[1] The cost for proper disposal of just one of the larger excess IRSs at a surveyed Radon plant in Russia was estimated at $90,000. A large-scale project to locate and dispose of all disused IRSs in Russia is not something that the Russian government has been willing to undertake, nor is it a project that is particularly feasible. Decisions on disposal, therefore, are made on a case-by-case basis.[1] Lack of funding has led to poor physical protection of their offices, staff deficiencies, inadequate training opportunities, and a lack of standardized documents that govern their activities and interactions with other organizations. All of these issues are fixable given proper funding and support, but without that, the IAC networks will continue to be inadequate in controlling and accounting for IRSs throughout the country.[1]

In addition to network and control issues, some serious physical security problems were highlighted in the above-mentioned 2007 Committee on Opportunities for U.S.–Russian Collaboration report. During a joint 2004–2005 survey of radiological facilities between the committee and IBRAE, at least five of the sites visited had serious security flaws.[1] Several of these sites had extremely poor security, allowing relatively easy access for potential thieves. One such facility was subject to flooding, which adversely affected the strength of the doors and walls. This facility also contained over 20,000 curies of Co-60 and was located 300 meters from a school, apartment complex, and other facilities.[1] IBRAE noted that, of the dozens of facilities that had been visited, a majority had adequate security.[1] However, the negative examples provided by the committee raised a great deal of concern. A determined thief or group of ill-willed individuals could have broken into any of these facilities without great difficulty and stolen a troubling amount of radioactive material. However, as this report is over 10 years old, improvements to these facilities' security may have since been made.

While these conditions do not necessarily represent the vast

majority of facilities throughout Russia, unwanted IRSs have little value, making them less likely to be adequately secured. Russia has shown on several occasions that radiological source security is not a high priority. Most recently, at the 2014 Nuclear Security Summit — at which a Russian delegation was in attendance — 23 countries signed a declaration of intent known as the Joint Statement on Enhancing Radiological Security. This joint statement supported the creation of an international regulatory body, comprehensive and cohesive security plans, international cooperation, a framework for facility security, and holistic regulatory frameworks for source transportation, possession, and disposition. Russia did not endorse this statement, despite being one of the world's largest producers of radiological source material.[9]

Consequences of a Radiological Terrorist Attack

Why would a determined actor want to launch a radiological terrorist attack when there are many potentially simpler methods to wreak havoc? The potential for substantial economic damage could be one driving factor behind launching a radiological terrorist attack. Such attacks are often referred to as weapons of mass *disruption* because the resources that would need to be dedicated to cleaning up the dispersal of high-activity radioactive material, especially in an urban place with high traffic or a large population, would be immense. A radiological attack could severely disrupt the safety of any nearby businesses, government offices, medical facilities, or transportation centers, which could spiral into significant local or regional economic damage. Economic damage could reach into the range of billions of dollars when incorporating recovery costs such as relocation, compensation, and health care; business costs in terms of economic activity impact; and perception costs, which could include a diminished willingness to purchase goods and services or invest in the affected area.

The economic consequences of an RDD event are highly dependent on the cleanup level selected. As there are no standards for acceptable decontamination of a radiological weapon event,[10] the standard selected will impact both the cost and the pace of the cleanup. For example, a substance such as caesium-137 with a 30-year half-life would potentially require waiting at least six or seven half-lives, or about 200 years, until the material has decayed to very small amounts. For example, in Chernobyl, it was determined to be cheaper to create an exclusion zone than to clean up to a publicly acceptable level. If there is a radiological terrorist event and the cleanup standard is "negotiated" after the incident, it is likely that the public will demand the most stringent level for decontamination. This will result in the highest costs for cleanup.

Widespread panic would most likely occur among at least the local population,[11] which could also lead to infrastructure overload, especially with regard to medical facilities. Hospitals, clinics, pharmacies, and government facilities would be overloaded with terrified people and potential patients. This could in turn prevent people in other emergency situations from getting the help that they need.[12]

Lost or Stolen Sources and the Potential for Terrorist Interest in RDD Materials

Information reported to the IAEA Incident and Trafficking Database confirms the persistent theft and loss of radioactive sources. The recovery rate of stolen or lost radioactive sources has been poor. The possibility that some of this radioactive source material is being trafficked cannot be excluded. In its Global Incidents and Trafficking Database, the Middlebury Institute of International Studies reports that in 2013 and 2014, there were 325 incidents in which nuclear and radiological material was lost, stolen, or otherwise determined to be outside of regulatory control. Most (about 85%) of recorded incidents in the database involved non-nuclear material, or the ingredients for a dirty bomb.

All of these challenges are against the backdrop of an evolving threat environment, whereby the likelihood of a dirty bomb attack is increasing. Terrorist organizations have demonstrated the potential for a worldwide reach. Using social media, they can recruit fighters and supporters from around the world. The terrorist attacks seen in cities around the world also point to disturbing trends. Domestic terrorism has increased over the past several years, and attacks are being carried out with a trend toward smaller and less-complicated plots. An RDD could fit this scenario.

Several violent actors could seek to launch an attack like this — either in Russia, or using Russian-made radiological materials. Among the possible perpetrators are Chechen extremists. The Chechen people of the North Caucasus region of Russia have long had issues with the Russian government, leading to war twice since the fall of the Soviet Union. An ISIS or al-Qaida affiliate organization or person could also potentially attempt an attack of this nature. As ISIS continues to lose territory throughout Syria and Iraq, a trend is starting to emerge where more and more militant fighters are returning home. According to estimates by the Soufan Group, Russia is responsible for approximately 2,400

foreign fighters taking part in the Syrian Civil War, making it the largest non-Arab contributor to foreign fighter numbers.[13] As more foreign fighters return to Russia, the threat may grow.

However, even if an attack is not perpetrated in Russia, there is still risk that unsecured Russian-made radiological material could fall into the hands of ISIS or al-Qaida via smugglers or criminal organizations. This situation has presented itself several times, most recently in November 2015 in Moldova when a smuggler named Valentin Grossu was caught attempting to sell a significant amount of caesium-137 to an ISIS representative. Grossu claimed that he was in possession of enough caesium-137 to contaminate several city blocks and was attempting to sell it for €2.5 million. This was the latest of at least four attempts since 2010 in which criminals with suspected ties to Russia attempted to sell radioactive materials to extremists through Moldova.[14] In April 2009, three people were arrested in Western Ukraine attempting to sell 3.7 kg of radioactive material for $10 million. The Ukraine Security Service determined the radioactive material to be of Soviet origin and that it had been smuggled into Ukraine for sale.[15]

Organized crime and corruption, especially in the closed nuclear cities of Russia, is not a new development. A December 2005 policy memo from the Program on New Approaches to Research and Security in Eurasia came to the troubling conclusion that "there are increasing threats that terrorist groups could use existing criminal networks and corruption to steal nuclear materials." Many of these existing criminal networks and smuggling routes into and out of closed nuclear cities such as Ozyorsk stem from a largely ignored drug problem. In 1999, the closed city of Ozyorsk in the Chelyabinsk Oblast had the most drug users per capita in Russia.[16] While that number may have fallen over the past 17 years, these drug-smuggling channels remain open. Rampant corruption, combined with opportunities to exploit workers and citizens of closed cities, provide terrorist organizations and transnational organized crime groups with a window to nuclear and radiological material smuggling.

There is also the risk of a lone-wolf attacker or unaffiliated group launching an attack in Russia or abroad with Russian materials. Although there have been no documented successful radiological attacks by a lone wolf in Russia, these attacks are much harder to detect or prevent. However, potential incidents have been caught before.[17]

Conclusion

Although much has been done between the United States, Russia, and other international partners to address the issue of Russian radiological material security, there remains much to do. An unknown amount of IRSs are located throughout the country in varying states of use. Facilities housing some of these materials have inadequate security and protection. Every year, incidents of unauthorized possession, loss, or smuggling of these materials occur. As of December 2014, no new bilateral cooperation is planned between the United States and Russia on the state of Russian radiological security. This has direct implications for threat mitigation investments that the United States and other countries have provided Russia over the past decade and whether complacency, competing budget priorities, and other factors have led to the erosion of security measures put in place. With the scope required to address cradle-to-grave radiological security, the concern is that this will not be a high priority for Russia and the work will not continue.

Although the Russian Federation has made a political commitment to the IAEA Code of Conduct on the Safety and Security of Radioactive Sources, little transparency and reporting on the status of Russia's radiological security efforts is shared with other member states.[18] This lack of transparency and reporting is further complicated by the cessation of U.S.–Russian Federation bilateral cooperation. Without significant bilateral or multilateral cooperation, Russia is unlikely to fully undertake this task. International support is imperative if this threat is to be properly mitigated. U.S.–Russian Federation radiological security demands a new paradigm for advancing radiological security cooperation. It is in our mutual interests.

Keywords

Radioisotope thermoelectric generator, radiological source security, Russia, terrorist attack

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The views expressed in this paper are those of the authors and do not necessarily reflect the views of NTI officers, staff, or the NTI Board of Directors, or the institutions with which they are associated.

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5. Logistics for RTG removal vary greatly depending on region, climate, and cost effectiveness and are subject to issues such as equipment availability, climate- and terrain-specific accessibility, and, in some cases, wildlife interference. As of today, 536 alternative power sources have been installed at selected sites.
6. Hallock A. 2014. Radiological security cooperation in the former Soviet Union. Presented at: *28th Plenary Meeting of the IAEA Contact Expert Group*; 2014 Nov 19; Rome, Italy
7. It is worth nothing that, as a major producer of sources, Russia exports lots of materials to other countries and refuses to take back these sources when they reach the end of life. The IAEA has recently finalized a Supplemental Guidance Document on this topic, and Russia was the only country that tried to stop the process. The absence of a "return to supplier" provision in Russia's laws, as well as the position that the country will not take back anything considered "waste," resulted in other countries struggling to deal with these materials when they are no longer in use.
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10. For example, in the United States, there are only recommended evacuation/relocation Protective Active Guidelines established by the Environmental Protection Agency and the Department of Homeland Security (2 roentgen equivalent man (rem)/year).
11. Anyone within relative range of the attack would fear for both their immediate and long-term health. Areas could be abandoned for a significant period of time, leaving people without homes or jobs. Media outlets would be covering the attack for quite a while, not allowing it to leave public consciousness. It is extremely difficult to convince large groups of people that they are safe in the wake of an attack, especially one that could have lasting consequences.
12. Any casualties would likely be caused by the initial blast of the conventional explosive. In most plausible scenarios, the radioactive material would not result in acutely harmful radiation doses, and the public health concern from the radioactive materials would likely focus on the chronic, or long-term, risk of developing cancer. Long-term health effects are possible for people directly exposed to the dispersed radiation; however, if the radiological material is dispersed in respirable form, those risks are much higher.
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17. In April 2016, a man left a package containing 5 ampoules of Cobalt-57 and concentrated Radon in a car parked in Vnukovo International Airport. The material was detected by sensors and was removed from the lot.
18. During the 2014 Nuclear Security Summit, Russia provided a National Report indicating laws and regulations on accountability, control, and physical protection of radioactive sources, and materials are being constantly improved – taking into account both national experience in this area and the experience of foreign states and international organizations, including the IAEA. Thus, in 2012, revised federal norms and rules entitled "Principal Rules for Accounting and Control of Radioactive Materials and Radioactive Wastes in Organizations" were approved, setting requirements on accountability and control, taking into account, inter alia, the ranking of radioactive materials based on their potential to cause harm. In 2014, revised federal norms and rules entitled "Rules Regarding Physical Protection of Radioactive Materials, Sources and Storage Facilities" were adopted. The radioactive source register is being kept and improved.

Nondestructive Analysis of SAVY Containers: Application of Nondestructive Testing to Assess Corrosion Damage

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Abstract

Stainless-steel SAVY containers are widely used at the Los Alamos National Laboratory (LANL) Technical Area TA-55 for long-term storage of nuclear materials. Recent surveillance activities completed have shown that these SAVY containers are prone to interior corrosion while in use due to a number of factors, such as decomposition of the poly-vinyl chloride bag-out bags and radiolytic hydrogen chloride gas generation. There is a strong need to develop nonintrusive inspection techniques that can monitor these corrosion processes in real time and in situ. Nondestructive testing (NDT) and procedures for assessing corrosion within SAVY containers are being developed to augment current destructive container monitoring and testing procedures. An earlier trade study completed at LANL narrowed down the choices to ultrasonic testing (UT) and eddy current array (ECA) testing. The two NDT methods were validated for SAVY container surveillance through controlled corrosion experiments and simulated pit creation. Pitting corrosion has been observed during the surveillance of SAVY containers and is a form of extremely localized corrosion that takes the form of cavities. The results have shown that UT and ECA testing complement each other and can be used to determine corrosion on the interior surface as well as pitting. UT can accurately detect changes in wall thicknesses due to corrosion processes. The wall thickness measurements completed on the sides and base of the corroded containers using UT were within 6.3% of those measured using a contour measurement machine (CMM). These results are significant because they demonstrate that UT can be used in lieu of the CMM measurements, which are extremely accurate but time consuming and which require opening the containers prior to use. In addition, ECA can be used to determine pitting and cracking within the containers. The smallest detectable pit depth on a SAVY container was repeatably measured at 0.0762 mm (even though the detection limit of the technique is lower). Building on the UT and ECA in this study, an automated inspection system combining the two systems is being developed and can be used to generate color-coded contour and damage plots of the interior of each SAVY container.

1 (a)

1(b)

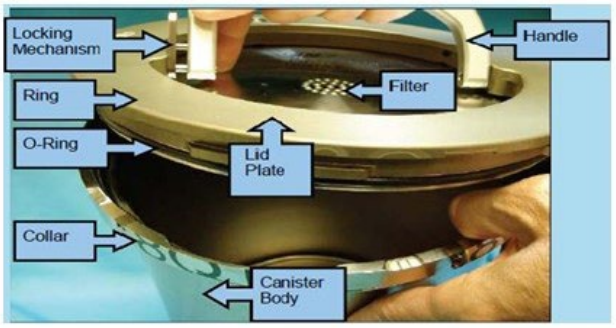


Figure 1. SAVY containers used for nuclear material storage at Los Alamos National Laboratory. (a) SAVY containers are available in various sizes, from 1 quart to 10 gallons. (b) The containers have various components, including a locking mechanism, HEPA filter, and a folding handle.

Introduction

The Department of Energy (DoE) issued DOE M 441.1-1, the *Nuclear Material Packaging Manual* in March 2008 to protect workers who handle nuclear material from exposure due to loss of containment of stored materials. The *Manual* specifies a detailed approach to achieve high confidence in containers' ability to contain the material and includes requirements for container

design and performance, design-life determinations, material contents, surveillance, and maintenance to ensure container integrity over time.

Nuclear Filter Technology, Inc., and the Los Alamos National Laboratory co-developed the SAVY 4000 container as a simple, robust, and reusable container for storing solid nuclear materials (see Figure 1). (The acronym SAVY represents the surnames of the four co-developers: Stone, Anderson, Veirs, and Yarbro.) The 316L stainless-steel SAVY 4000 series of containers includes seven sizes (1, 3, 5, 8, and 12 quarts; 5 gallon; 10 gallon) and will replace the current Hagan-style containers of the same sizes. The design of this container include a high-efficiency particulate air (HEPA) filter to prevent pressurization and to facilitate the release of hydrogen, thus preventing flammable gas mixtures from forming within. The filter also prevents radiological particulate release.

The SAVY container must undergo physical testing for compliance with DOE M 441.1-1 and 49 CFR 173.465 requirements for safe storage and transportation of nuclear material. On average, 15 SAVY containers are selected annually for destructive testing. Although extensive mechanical and destructive testing (including drop testing; see Figure 2) is conducted on these containers in compliance with DoE requirements, these testing methods do not determine the condition of the SAVY containers in situ. The mechanical damage to the containers (such as dents or plastic deformation) resulting from the drop tests can be evaluated by metallographic techniques coupled with structural analysis; however, interior damage resulting from mechanical and corrosion processes cannot be quantified in real time. Furthermore, mechanical testing requires repackaging, decontamination, and removal of the containers from the glove box lines. The current testing processes are tedious, costly, and time consuming. They also do not indicate (in real time) whether the corrosion within the containers is at a level that might compromise the integrity of the container and facility safety.

Once physical testing (destructive) is initiated, the SAVY container is no longer in compliance with DOE M 441.1-1 and 49 CFR 173.465 standards due to its unknown structural integrity, thus terminating the continued use of that container (at a cost). There is a strong technical, financial, and environmental need to develop nondestructive techniques for analyzing plastic deformation and corrosion of SAVY containers. Such techniques must provide efficient and accurate information on the structural integrity of SAVY containers. This in turn will maximize the economic value of SAVY containers.

An objective, design-criteria-oriented feasibility assessment of relevant nondestructive testing (NDT) techniques was completed as part of an earlier trade study.[1–7] Nine NDT techniques were evaluated against a total of 11 criteria (five technical and six operational). The technical criteria included accuracy, precision, detection limits, surface compatibility, and the ability

Figure 2. Examples of SAVY containers after drop testing was performed in compliance with regulations DOE M 441.1-1 and 49 CFR 173.465 requirements. External damage can be quantified; however, internal damage and cracking due to mechanical and corrosion processes cannot be determined using current destructive test methodologies.

to interrogate the interior surface. The operational factors included ease of use, processing time, equipment costs, criticality risks, portability, and user safety. Weights were assigned to each of the 11 criteria using a combination of the analytic hierarchy process and the quality function deployment method. Each of the nine NDT processes was ranked against each of the 11 criteria.

High-frequency ultrasonic testing (UT) and eddy current array (ECA) were chosen following the technical and feasibility study of NDT methods, along with consultation with industry experts. UT ranked highest in surface corrosion detection (wall thickness changes), whereas ECA ranked highest in mechanical damage and corrosion pitting assessment. This study will discuss the results of the nondestructive measurements performed using these two down-selected methodologies.

Methods

Instrumentation

Commercial off-the-shelf NDT systems were selected to reduce the overall development time and to focus efforts on adapting these technologies to nuclear storage applications. An Olympus 38DL Plus handheld UT unit with a Sonopen transducer and an Olympus OmniScan MX eddy current system with 32 transducers were used for the initial experiments.

The Olympus Sonopen UT transducer uses a single piezoelectric element to transmit acoustic signals into a material and receive those signals. It operates at a frequency of 15 MHz and features a plastic delay line (as part of the transducer). High-frequency transducers are more sensitive in thin-wall applications, and a delay line further decreases the minimum measurable wall thickness.[4] The primary function of the delay line is to introduce a time delay between the generation of the sound wave and the arrival of the reflected wave. This allows the transducer to complete its "sending" function before it starts its "listening" function. This decreases interference and significantly improves near-surface resolution. The local scan spot size (diameter) of the Sonopen transducers is 3.175 mm. Additional equipment details can be found elsewhere.[8]

The OmniScan MX ECA Testing system, which integrates 32 individual eddy current generating elements, was used. These coils form an ECA array, enabling the capability for 2-D mapping (C-scans). The OmniScan acquires data from the ECA with a maximum potential of 12 volts, up to 360° phase rotation, and an operating frequency between 20 Hz and 6 MHz. Other details related to the equipment used can be found elsewhere.[9]

ECA uses an alternating current that is introduced within a magnetic field. When the coil within a probe is placed onto a conductive material, an opposing alternating current is generated. If there are defects within the conductive material, the defects disrupt the eddy current field, and the disturbance is detected and analyzed. This technique has the ability to electronically drive multiple eddy currents within the same probe, and thus data acquisition is performed by multiplexing eddy current coils in a specific pattern.[6]

Experiment Description

Baseline thickness measurements were completed on flat plate samples and on new 3-quart and 5-quart Hagan and SAVY containers. In addition, several experiments were designed to understand the capabilities and test the instrumental response of the technologies chosen as part of the initial trade study.[1] First, each technique's detection capabilities were tested on flat, 316L stainless-steel plates. The plates were obtained from the manufacturer of the 316L stainless-steel alloy used for SAVY containers (including the heat treatment cycle) and had the same average thickness (0.762 +/- 0.03 mm) as the SAVY containers. These stainless-steel 316L plates were subjected to varying degrees of corrosion using hydrogen chloride (HCl) and ferric chloride ($FeCl_3$) at 25°C, 5% relative humidity, 660 mm Hg absolute pressure. Samples were subjected to three concentrations of HCl at room temperature — namely, 8M, 10M, and 12M. Two concentrations of $FeCl_3$ (1.5M and 3M) were also used for these preliminary experiments. These two chemicals were chosen because of their presence within the facility in various processing operations.

Figure 3 shows the experimental setup. The corrosive solutions are located within the glass tubes, and the 316L plates are at the bottom of the assembly. The volume of the corrosive liquids in the tubes was 50 cc. The stainless-steel samples were exposed uniformly to the corrosive liquids. Wall thickness measurements were completed every 12 hours (for a total of 168 hours) using both UT and a calibrated micrometer. The results of this experiment were used to determine the NDT's measurement capabilities with regards to wall thickness measurements as well as its overall performance on corroded samples.

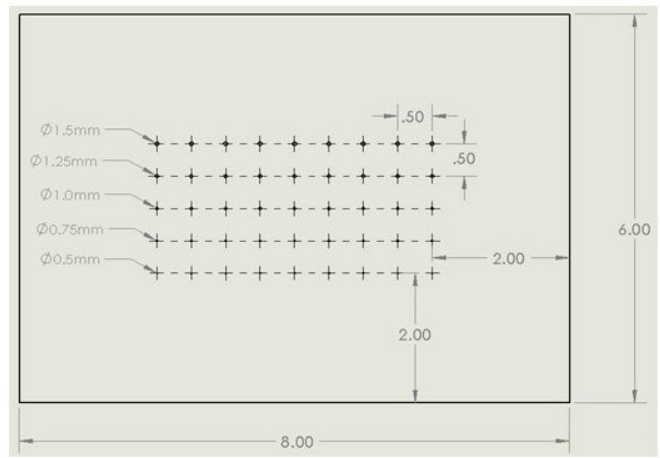
Figure 3. Setup used to complete the corrosion experiments. The hydrogen chloride (HCl) and ferric chloride ($FeCl_3$) solutions are in the columns and were applied to one side of the 316L plates. (The mixture of hydrogen chloride [HCl] and hydrogen peroxide shown in the middle was not used because the response of the 316L to the solution was similar to that of HCl alone.)

Figure 4. One of three corroded containers extracted from use as part of the surveillance program. This container had been in service for 13 months storing nuclear materials in an acidic environment. This container was inspected by the chosen NDT techniques.

In the second experiment, three corroded SAVY containers and a control were made available for testing by the container management team (see Figure 4). The SAVY containers had been in service for 13 months and had been used to store nuclear material in an acidic environment. Wall thickness measurements were conducted on both the corroded and control containers using a contour measurement machine (CMM), and the results were compared to those obtained by NDT. The goal here was to determine whether the corrosion was detectable by the chosen NDT technique. These measurements also allowed us to determine if pitting corrosion could be specifically detected on these containers (through analysis of the signal attenuation). The goals of this experiment differed from the first experiment in several important ways; it was important to test whether the given NDT technique could operate successfully on curved surfaces as opposed to flat surfaces. Second, these containers had not been subject to high concentrations of corrosive agents; rather they were a product of normal storage conditions. Demonstrating success in this experiment was critical for the chosen NDT technique to be viable in the application environment.

Finally, it was determined that pitting corrosion observed on containers in use may be especially detrimental to the integrity of SAVY containers. This warranted a separate set of experiments. To achieve artificial pitting, the plate samples were exposed to a 1.5M solution of $FeCl_3$ for extended periods of time (48–168 hours). Extensive pitting occurred and was recorded on these samples.

To baseline the pit measurement capabilities of the two non-destructive evaluation tools, an additional experiment was conducted. This experiment aimed to determine the smallest pit



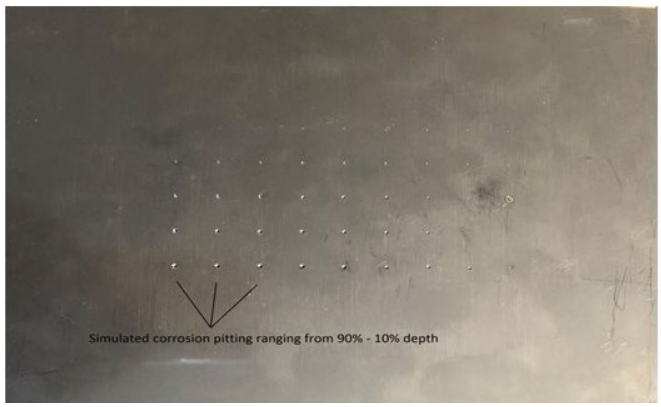


Figure 5. Schematic (above) and photograph (below) of the 316L test plate with simulated pits. The depth of each pit ranged from 10% to 90% of the wall thickness, or 0.0762 mm to 0.6858 mm. Larger external dimensions of the plate are in inches.

Table 1. Comparison of the UT and CMM measurements performed on the 3-quart and 5-quart Hagan and SAVY control containers. All measurements are in millimeters, and differences are in percent. The red entries for axis A and the center at the bottom of the 3-quart Hagan was an anomaly because of a sticker attached to the bottom of the container that could not be peeled off.

HAGAN 3 QT Serial # 300076

	AXIS A			AXIS B			AXIS C		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
Top (Open End)									
1	0.72	0.733	1.77	0.72	0.724	0.55	0.72	0.727	0.96
2	0.69	0.705	2.13	0.69	0.706	2.27	0.69	0.695	0.72
3	0.68	0.679	0.15	0.66	0.679	2.8	0.67	0.687	2.47
4	0.66	0.683	3.37	0.66	0.672	1.79	0.66	0.68	2.94
5	0.66	0.674	1.4	0.65	0.669	2.84	0.66	0.673	1.93
Avg.			1.764			2.05			1.804

	AXIS A Bottom			AXIS B Bottom			AXIS C Bottom		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
	0.59	0.6	1.67	0.58	0.593	2.19	0.58	0.586	1.02
	0.59	0.598	1.34	0.59	0.6	1.67	0.59	0.598	1.34
0.61(S)		0.689(S)	11.46	0.58	0.587	1.19	0.58	0.582	0.344
			1.505			1.68333			0.90133
			Center 0.6(S)--SONOPEN and 0.685(S)--CMM						

SAVY 3 QT Serial # 111603079B

	AXIS A			AXIS B			AXIS C		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
Top (Open End)									
1	0.72	0.73	1.37	0.71	0.723	1.79	0.74	0.76	2.63
2	0.68	0.702	3.13	0.69	0.706	2.27	0.72	0.73	1.36
3	0.66	0.683	3.37	0.68	0.696	2.3	0.69	0.712	3.09
4	0.66	0.688	4.07	0.67	0.695	3.6	0.68	0.702	3.14
5	0.68	0.696	2.3	0.68	0.696	2.29	0.68	0.697	2.44
Avg			2.848			2.45			2.532

	AXIS A Bottom			AXIS B Bottom			AXIS C Bottom		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
	0.61	0.627	2.71	0.61	0.63	3.17	0.61	0.627	2.71
	0.61	0.628	2.87	0.61	0.627	2.71	0.6	0.623	3.69
	0.61	0.62	1.61	0.61	0.622	1.93	0.61	0.625	2.4
			2.396667			2.60333			2.93333
			Center 0.6--SONOPEN and 0.62--CMM				3.22%		

HAGAN 5 QT Serial # 08/07-05047

	AXIS A			AXIS B			AXIS C		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
Top (Open End)									
1	0.76	0.777	2.19	0.76	0.774	1.81	0.79	0.8	1.25
2	0.73	0.745	2.01	0.73	0.738	1.08	0.75	0.766	2.09
3	0.71	0.72	1.39	0.71	0.713	0.42	0.73	0.732	0.27
4	0.7	0.704	0.57	0.69	0.691	0.14	0.71	0.717	0.98
5	0.69	0.695	0.72	0.67	0.691	3.03	0.7	0.712	1.69
6	0.68	0.686	0.87	0.66	0.672	1.79	0.69	0.701	1.57
7	0.68	0.69	1.45	0.65	0.674	3.56	0.68	0.694	2.02
Avg			1.31429			1.69			1.41

	AXIS A Bottom			AXIS B Bottom			AXIS C Bottom		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
	0.63	0.669	5.83	0.63	0.669	5.83	0.63	0.651	3.22
	0.63	0.665	5.26	0.63	0.664	5.12	0.64	0.653	1.99
	0.61	0.639	4.54	0.61	0.631	3.33	0.61	0.632	3.48
			5.21			4.76			2.89667
			Center 0.6--SONOPEN and 0.635--CMM				5.50%		

SAVY 5 QT Serial # 011705179B

	AXIS A			AXIS B			AXIS C		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
Top (Open End)									
1	0.74	0.753	1.73	0.75	0.772	2.85	0.78	0.799	2.38
2	0.71	0.722	1.66	0.72	0.732	1.64	0.74	0.769	3.77
3	0.69	0.703	1.85	0.7	0.71	1.41	0.72	0.736	2.17
4	0.68	0.702	3.13	0.68	0.697	2.44	0.71	0.718	1.11
5	0.67	0.687	2.47	0.68	0.699	2.72	0.69	0.705	2.13
6	0.68	0.677	0.44	0.68	0.706	3.68	0.69	0.711	2.95
7	0.66	0.669	1.35	0.63	0.695	9.35	0.68	0.696	2.29
Avg			1.80429			3.44143			2.4

	AXIS A Bottom			AXIS B Bottom			AXIS C Bottom		
	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)	SONOPEN	CMM	delta(%)
	0.58	0.592	2.03	0.59	0.586	0.68	0.58	0.608	4.6
	0.59	0.61	3.28	0.59	0.628	6.05	0.59	0.626	5.75
	0.57	0.588	3.06	0.57	0.598	4.68	0.57	0.597	4.52
			2.79			3.80333			4.95667
			Center 0.57--SONOPEN and 0.594--CMM				4.04%		

size detectable, particularly by ECA. A custom calibration plate was machined with indentations of varying diameters and depths to simulate different levels of pitting corrosion. Figure 5 shows a schematic of the plate. The ECA technique was applied to the area around each pit, and the results were recorded. The intent of this experiment coupled with the previous experiment was to answer two important questions: can the ECA technique detect pitting corrosion, and if so, what is the smallest detectable pit?

Results

Initial baseline thickness measurements were completed on control samples (flat plates) using UT, and the results were compared to those obtained from micrometer measurements. Five readings on the flat stainless-steel 316L samples were completed. The measurements from the two techniques were found to be in good agreement and were within 2.5% of each other. In addition, control (new) Hagan and SAVY containers (curved surfaces) were measured using UT, and the results were compared with those obtained from a CMM. The measurements completed on baseline 3-quart and 5-quart Hagan and SAVY containers have a relative error within 3.5% of the CMM measurements on the side wall, and within 5.5% along the base of the containers (see Table 1). Measurements on all four containers were completed along three vertical axes (A, B, C), each 120° apart. For the 3-quart Ha-

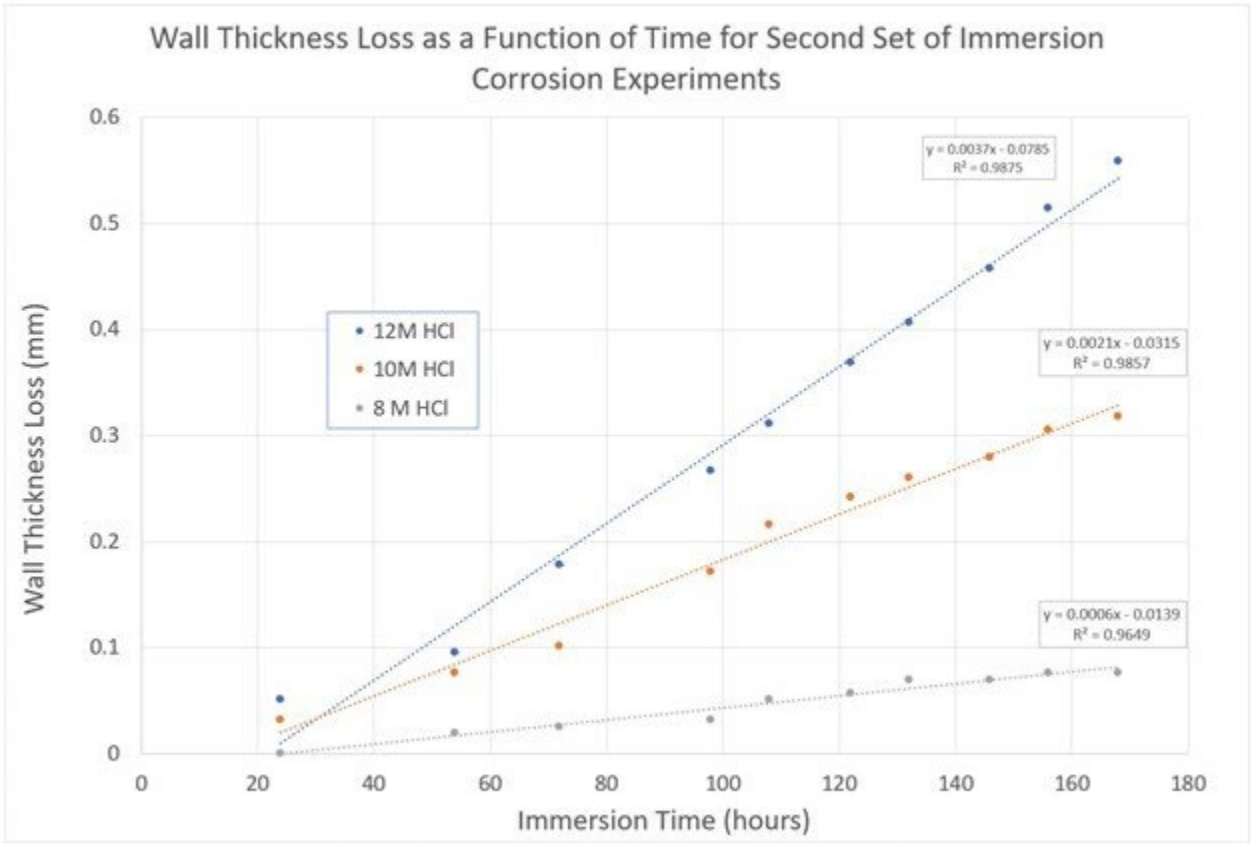


Figure 6. Wall thickness loss of thin 316L plates corroded with various concentrations of HCl over 7 days (168 hours). The points represent data collected by a UT gauge. However, the data from the UT gauge were within 2.5% of the values measured by a micrometer.

gan and SAVY containers, five equidistant points along the length were chosen; for the 5-quart containers, seven equidistant points were chosen. The base thickness was also measured using the same tri-foil pattern as the length — namely, axes A, B, and C, with three chosen points for each segment. The center of the bottom of the containers was measured separately. Because the containers' thickness varies from the top to the bottom and along the base, we used a point-to-point measurement to compare the results from the UT and CMM. These results confirmed UT as a valid method for completing thickness measurements on flat and curved surfaces.

The initial trade study had ranked ECA poorly as compared to UT for wall thickness measurements, and this conclusion was confirmed by experimental measurements. The ECA wall thickness measurements performed on the flat plate samples and the 3-quart and 5-quart Hagan and SAVY containers differed from the micrometer and CMM measurements by as much as 50%. The repeatability of the measurements was also very poor. As a result, the thickness measurements on the plate samples used in the laboratory corrosion tests were completed using UT alone.

Immersive corrosion tests on flat 316L plates were conducted using three concentrations of HCl. Figure 6 shows the results of the change in the wall thickness with time as a function of HCl concentration. As the corrosion progressed, a uniform loss of thickness with time was measured with the UT gauge. These measurements were taken at five different locations on the sample plate (and averaged); one at the end of each of the four quadrants, and the fifth measurement in the center of the sample. The results show a linear correlation with time for all three concentrations of HCl. Calibrated micrometer measurements were completed on these samples. These measurements were within 2.5% of those taken with UT. Even though the corrosion measurements were done on flat plates, similar trends are expected on curved surfaces. The solution concentrations used

in this experiment represent extreme conditions. SAVY containers would not be subject to this level of a corrosive environment in normal use.

Figure 7 is a representative optical micrograph of the 316L sample exposed to 12M HCl for 168 hours. The surface of the sample exhibits uniform corrosion. Similar surface features were observed on samples exposed to 8M and 10M HCl. The surface features did not change significantly with molarity and/or exposure times.

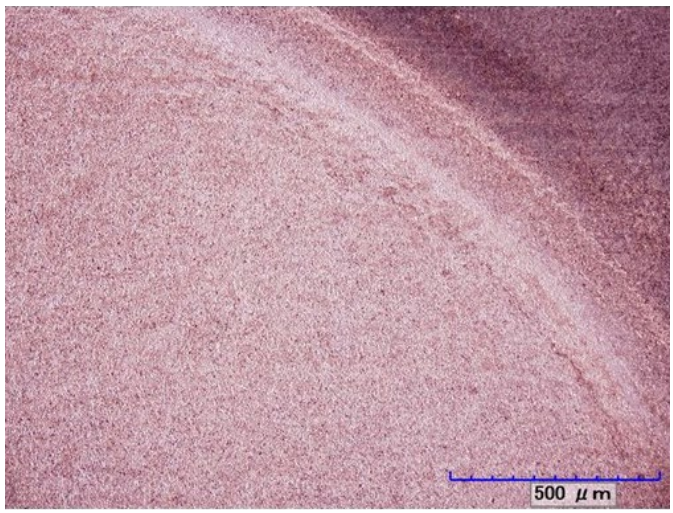


Figure 7. Digital microscope image of the edge of a circular region of a 316L plate treated with 12M HCl for 7 days.

By contrast, the corrosion occurring on samples exposed to $FeCl_3$ yielded radically different surface effects (see Figure 8). As referenced in many standardized corrosion tests, $FeCl_3$ produces pronounced pitting corrosion. These pitting effects were observed for both concentrations of $FeCl_3$. Notably, the 1.5M $FeCl_3$ yielded more localized and deeper pits on the samples as compared to samples exposed to the 3M $FeCl_3$. One sample treated with the 1.5M $FeCl_3$ was perforated in several locations after 60 hours of exposure. None of the samples treated with 3M $FeCl_3$ were perforated even after 168 hours of exposure, even though they exhibited extensive surface pitting.

The UT gauge could not perform wall thickness measurements on the samples corroded with either of the two concentrations of $FeCl_3$, due to extensive pitting. Pitting attenuated the acoustic signal, perhaps reflecting it askew from the detecting transducer. This phenomenon made traditional time-of-flight UT wall thickness measurements impossible. However, UT presents a possible go/no-go method of detection: areas that show attenuated signal likely indicate pitting corrosion. This signal gate methodology could be used to determine the point in time at which surface pitting begins. The UT transducer was rastered across the reverse side of a sample exhibiting highly localized pitting corrosion. Given enough time, this method can detect signals that resemble localized pits. However, this process was extremely time consuming and inefficient.

The UT was effective in measuring uniform wall thickness changes. Higher concentrations of HCl and longer exposure times yielded a faster loss of wall thickness and a greater total loss. The minimum accurately measurable wall thickness of the Sonopen 15 MHz transducer is 0.25 mm. Below this value, the initial pulse was too close to the back-wall echo, and the waveform changed dramatically, rendering the measurements inaccurate. We are in

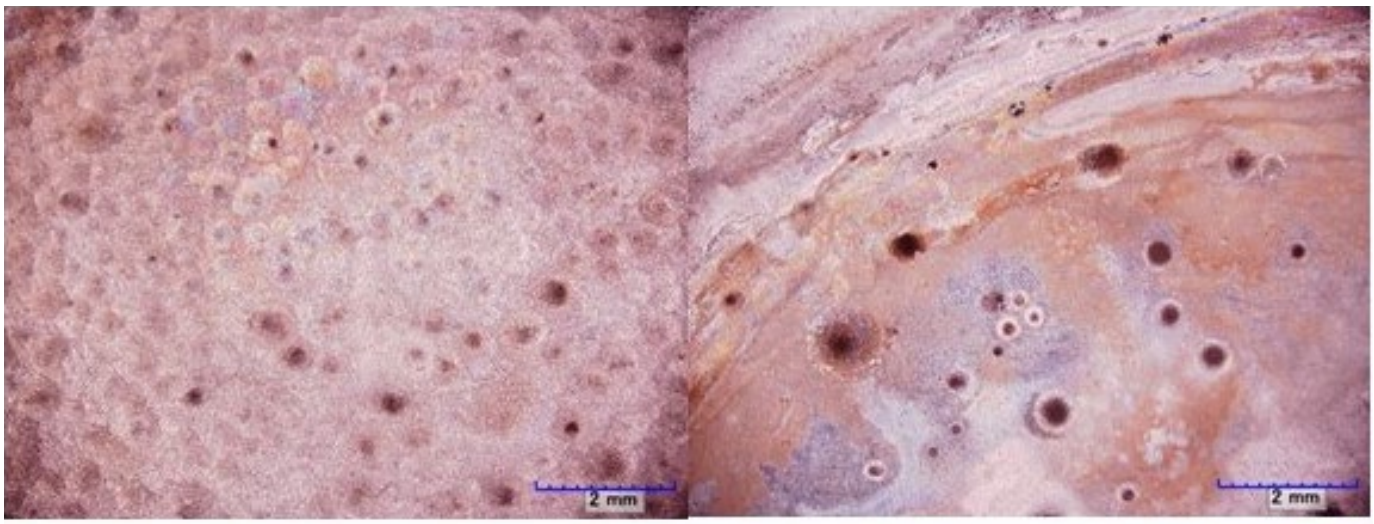


Figure 8. Samples corroded with $FeCl_3$ exhibiting pitting corrosion. The sample at left was treated with 3M $FeCl_3$, and the sample at right was treated with 1.5M $FeCl_3$.

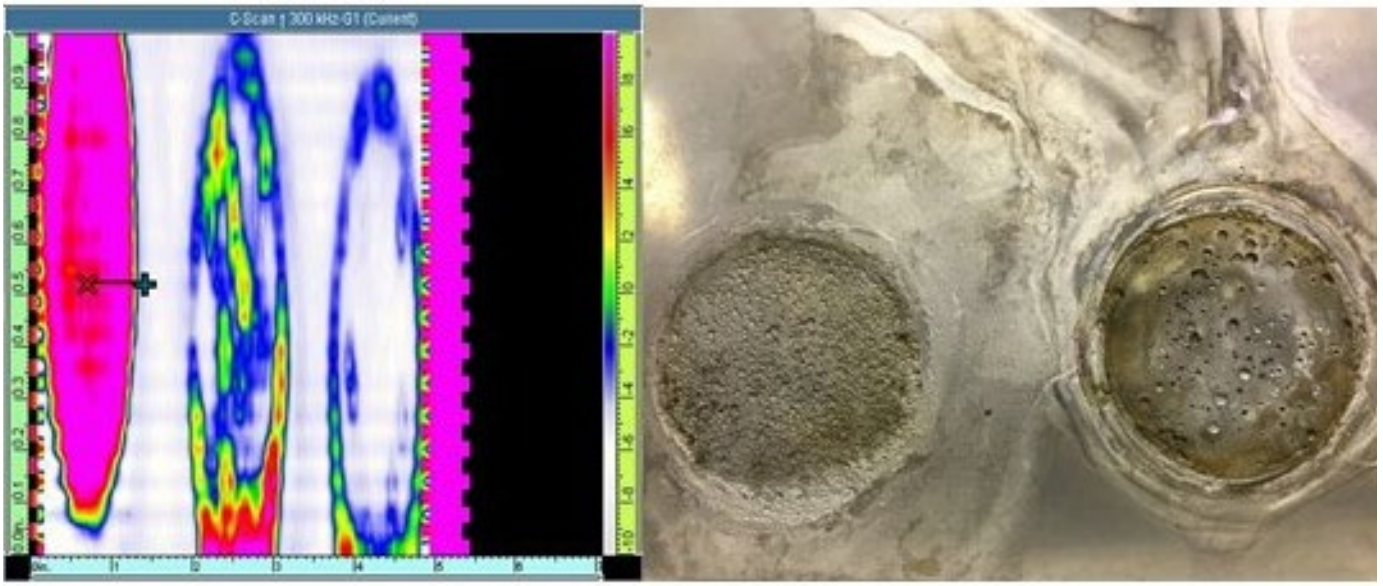


Figure 9. Example of ECA analysis of pitted 316L samples (right). The photograph on the right shows the 316L exposed to 3M and 1.5M $FeCl_3$. The image on the left is a composite of three different samples: a baseline sample (uncorroded; seen as mostly pink), the sample exposed to 3M $FeCl_3$ in the middle, and the sample exposed to 1.5M $FeCl_3$. The colors on the instrument can be adjusted to create a flaw (pitting) map.

the process of looking at smaller probes to measure thicknesses below 0.25 mm.

A total of 38 unique UT measurements on various pristine and corroded flat samples were completed and compared with their corresponding micrometer measurement to determine agreement and repeatability. The z-test is a statistical test used to determine whether two population means are different. A one-tailed z-test calculated that the mean difference between the values was less than 0.0175 mm at a confidence interval of 99%. These values indicate good agreement between the two techniques and highly repeatable wall thickness measurements.

As mentioned earlier, the ECA system could not detect changes in wall thickness for samples exposed to HCl. This was not surprising, because ECA detects mechanical deviations (flaws) and the samples exposed to HCl showed uniform corrosion. However, the ECA probe quickly and accurately identified localized pitting, generating a color-coded contour map of their location in the process (see Figure 9). To understand the ECA's capabilities and instrumental response, a custom calibration plate was accurately machined with indentations of varying diameters and depths ranging from 10% to 90% thickness of the plate to simulate different levels of pitting corrosion. Measurements were taken to quantify the smallest pit detectable by ECA analysis and to determine the limitations of the technology.

To accurately assess the controlled pitting using the ECA module, a scan of the controlled test plate was taken three times. The three scans were recorded, and the averages of each trial was taken. Table 2 shows the data represented by the phase angle. The phase angle was recorded and a linear regression was found in order to correlate the depth of a pit. Table 2 also shows the average of the three phase angle tests. Using the phase angle data, the depth was calculated using the trend line analysis. The theoretical versus calibrated depth was plotted, and standard deviation was calculated. The data was then fit linearly for a visual representation of the theoretical versus experiential values for depth of the simulated corrosion pitting (see Figure 10). The standard deviation and percent error of the experimental depths of the corrosion pit versus the actual values were taken to quantify the reliability of the

ECA Omni Scan MX. The standard deviation and percent error are listed in Table 2.

Even though agreement was obtained between the actual and measured data, the error is large. We believe that the large error is a result of machining artifacts. This error can be significantly

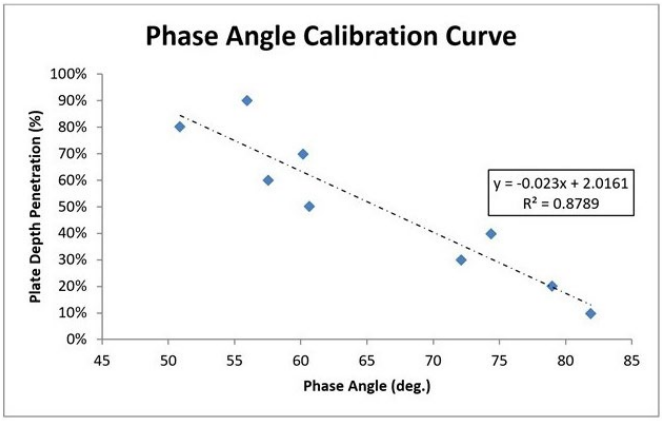


Figure 10. The measured phase angle plotted for each machined pit depth. The actual pit depths (percentage of plate thickness) are from the machined test plate.

Table 2. Results of the ECA measurements completed on the standard test plate. The phase angles for three measurements (at each depth) and the translation to the derogation depth can be seen above. The relative standard deviation and percent error are also listed.

Percentage Depth Degradation	Phase Angle (°)Test 1	Phase Angle (°)Test 2	Phase Angle (°)Test 3
90%	55.9	55.2	53.4
80%	50.9	51.6	52
70%	60.2	61.6	60.3
60%	57.5	56.8	58.2
50%	60.6	59.8	61.2
40%	74.4	76	73.5
30%	72.1	72.5	76.7
20%	79	79.1	79
10%	81.9	83	79.9

Derogation Depth (%)	Test 1 (mm)	Test 2 (mm)	Test 3 (mm)	Actual Depth (mm)
90%	0.5565	0.5689	0.6001	0.6858
80%	0.644	0.6319	0.6290	0.6096
70%	0.4813	0.4567	0.4795	0.5334
60%	0.5285	0.5407	0.5161	0.4572
50%	0.4742	0.4881	0.4637	0.381
40%	0.2324	0.2042	0.2319	0.3048
30%	0.2725	0.2657	0.1920	0.2286
20%	0.1516	0.1499	0.1517	0.1524
10%	0.1008	0.0815	0.1359	0.0762

Percent Depth	Standard Deviation (mm)	% Error
90%	0.0196	23.22
80%	0.0016	5.37
70%	0.0173	10.85
60%	0.0173	13.49
50%	0.0144	19.65
40%	0.00776	31.19
30%	0.00882	16.15
20%	0.00359	0.45
10%	0.0208	24.47

reduced through the use of better-machined and -calibrated test plates. The smallest detectable pit depth was 0.0762 +/-0.0015 mm. This sensitivity of the ECA technique can also be improved through baselining against better-machined standard test plates.

Three 5-quart SAVY containers that exhibited visible signs of surface corrosion after storing nuclear material for 13 months were compared with the unused control SAVY container. The maximum and minimum wall thickness of both the sides and bottom of the corroded containers were measured with a CMM. These same measurements were replicated with the UT gauge for comparison (see Table 3). The greatest relative error between the results obtained with UT vis-à-vis CMM measurement was 6.3%. This experiment demonstrates the accuracy of UT wall thickness measurements on the curved walls of corroded SAVY containers. Combined with the results from the previous experiment conducted with flat plates exhibiting advanced corrosion,

Table 3. Comparison of UT and CMM measurements performed on three corroded containers. The base measurements are critical to maintaining material containment.

	Longitudinal Measurement				Base Measurements			
Serial #	UT (mm)		CMM (mm)		UT (mm)		CMM (mm)	
	Max.	Min	Max	Min	Max	Min.	Max.	Min.
011305020B	0.762	0.56	0.813	0.67	0.61	0.56	0.602	0.592
081305070B	0.787	0.53	0.828	0.68	0.58	0.53	0.594	0.554
091205141B	0.787	0.56	0.803	0.68	0.58	0.53	0.607	0.533

Measurement	Greatest Relative Error (%)
Longitudinal	6.3
Base max.	3.7
Base min.	5.6

and the baseline measurements completed on the pristine containers, UT wall thickness measurements are a capable and accurate indicator of wall thickness loss as a result of corrosion.

ECA was used to determine pitting on the inside of the container. Given the agreement from the standard plate experiment, we were able to quantify somewhat the pitting on the inside of the containers. The ECA accurately located and identified pitting on the inside of the SAVY containers. The location of the pitting was validated through microscopy. Even though the smallest pit diameter detectable was tagged at 0.0762 mm, we believe the technique has the capability of detecting smaller pits. Further studies are needed in this regard and are currently underway.

Conclusions

This is the first documented study of the potential use of NDT to measure in situ, real-time corrosion in SAVY containers. The experiments performed on corroded test plates as well as corroded SAVY containers (extracted as part of the surveillance program), demonstrate the ability of using UT and ECA to complete NDT on SAVY containers. UT provides reliable and repeatable wall thickness measurements even on the curved walls of corroded SAVY containers. Actual container measurements combined with the results from the laboratory corrosion experiments conducted with flat plates demonstrate that UT wall thickness measurements can be used to measure wall thickness loss as a result of corrosion. Pitting corrosion makes traditional time-of-flight UT wall thickness measurements inaccurate and often impossible. However, UT presents a possible method of screening: areas that show an attenuated signal likely indicate pitting corrosion.

ECA met the trade study criteria by fulfilling the list of requirements and was chosen as the primary technology for assessing flaws within SAVY containers. The use of the trend line equation made it possible to derive the depth of the simulated corrosion pitting. The ECA technology can detect a pit measuring at least 0.0762 mm in depth (the smallest manufactured pit). The decrease in precision of the measurements of simulated pits in the 316L stainless-steel plate is represented in the data by a greater standard error for the experimental data verses actual values. Using a calibration block reduces the error, and the ECA technique yields a 5% error from the calibrated values vis-à-vis measured values. The ECA technique can be fine-tuned and tailored to make measurements smaller than 10% derogation using more specific geometries, material properties, and a more precise calibration block than the 316L stainless-steel plates used in the current experiment.

The two nondestructive tests, UT and ECA, show tremendous promise in measuring corrosion within Hagan and SAVY containers and will complement each other in an automated inspection system (see Figure 11). Such a test setup will be used to generate, for each container in real time, color-coded corrosion

Figure 11. Proposed test setup for completing the nondestructive evaluations of the Hagan and SAVY containers. (a) Cart with the entire measurement setup, (b) raster base for the ECA, (c) multi-Sonopen assembly rack, and (d) plan view schematic of the adjustable baseplate to accommodate various container sizes.

plots. The test setup will include UT and ECA probes on a single platform. This platform has been designed to accommodate multiple sizes of containers (both Hagan and SAVY). In addition, UT testing will be completed using a multiplexed UT Sonopen system to accelerate field testing. The ECA probes will be rastered over the surface, bottom, and corners of the containers. The data acquired from such a system will enable rapid visual inspection and flaw detection, with each container serving as its own control. An automated NDT system will reduce the amount of time workers are in radiation areas, increasing worker safety as well as improving surveillance cycle efficiency. More frequent surveillance of at-risk containers, creation of a detailed record of each container, and long-term data collection for lifetime certifications will be possible.

We are in the process of establishing the effect of reduced wall thickness and corrosion pit size/distribution on the mechanical strength of the Hagan and SAVY containers. This data will be crucial in setting the acceptance criterion for container degradation to be measured using NDT.

Keywords

Nondestructive testing, nuclear material storage, SAVY containers

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Taking the Long View in a Time of Great Uncertainty

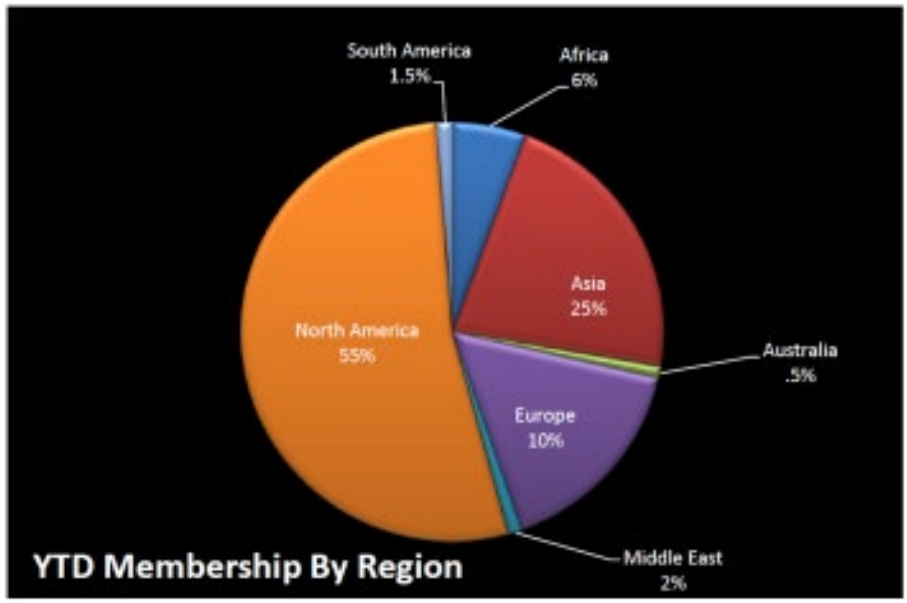
Listening to Our Members and Advancing INMM's Mission in the Midst of Global Turmoil

Jack Jekowski
Industry News Editor and Chair of the Strategic Planning Committee

The world and the Institute of Nuclear Materials Management (INMM) are experiencing turmoil on an unprecedented level, with respect not only to "things nuclear" but also many other technological, societal, and political influences that directly or indirectly impact the world that INMM operates in and that our membership finds itself facing every day.[1]

In the closing plenary at the 2018 Annual Meeting, the Institute solicited input from attendees on a number of strategic subjects,[2] stimulated by initial discussions from a panel of experts[3] who also offered their opinions on the topics identified by the Executive Committee (EC) prior to the meeting.[4]

During this past year, the EC has analyzed the information gathered from that closing plenary session and put it into context with the Institute's existing Strategic Plan.[5] As might be expected, the number one issue identified by our membership in each of the strategic subjects discussed can be directly tied to the turmoil that we all see around us every day. This column summarizes the top priority in each strategic subject area discussed at the closing plenary session, demonstrating the breadth of the subject matter expertise in our Institute and the broad interests of our members.[6]



Lack of Political Progress on Nuclear Disarmament

How do we deal with the "new normal" with respect to arms control negotiations (or lack thereof)? With the withdrawal from the Joint Comprehensive Plan of Action by the United States, the abandonment of the Intermediate-Range Nuclear Forces Treaty by both the United States and Russia, and the ambivalence about extending the New Strategic Arms Reduction Treaty, years of work to establish some modicum of nuclear arms control appears to be fading away. Another challenge to the Institute is how we recapture engagement of the Russian chapters and continue to make the work of the Institute relevant and value-added to our other international members. Should we consider holding INMM events or workshops in Europe or Asia to reengage them in the Institute's activities?

The most recent data shows that our membership is now almost equally balanced between U.S. and international membership. This is a historic milestone and requires bold thinking to address the changing demographics of the Institute. Nuclear materials management is indeed a global issue, and INMM members are the experts at the table. So how do we leverage that expertise?

Implementation and Security Practices at Sites

Although physical perimeter security at sensitive nuclear sites, including nuclear power reactor sites, is still a critical issue of concern with policymakers and the public, new technologies such as drones and cybersecurity have captured much of the headlines today.

Some Institute members expressed concerns about "less-attractive" sites such as university research facilities where funding for security may not be adequate to protect against potential threat scenarios. Much work has been done over the past two decades — most recently, during the Obama administration's Nuclear Security Summit years — to reduce the

opportunities for diversion or sabotage by reducing the amounts of nuclear materials and the number of sites worldwide. For the plenary attendees to identify this as the highest challenge, risk, or threat with respect to nuclear security clearly demonstrates that something still is not right.

At one time, the Physical Protection Division (now named the Nuclear Security and Physical Protection Division) was one of the most active INMM technical groups. This was driven in large part by congressional hearings in the United States (such as the Dingle Commission), as Sandia and other national laboratories designed and deployed sophisticated perimeter-intrusion systems and developed techniques such as vulnerability analysis to categorize threats and identify solutions. It was noted that much of the U.S. infrastructure still uses decades-old technologies, some of which failed the simplest of tests, as demonstrated by the 2012 intrusion at the Y-12 National Security Complex. Is it again time for a major technology development program to emerge? Where are the papers at our Annual Meeting proposing such technologies?

Ability to Interfere with Safety Systems at Facilities

All of the responses demonstrated that our membership is concerned about the cyber threat to nuclear facilities and systems, with the highest interest associated with safety issues. The recent action by the EC to create the Cyber/Physical Security Integration Committee reflects an acknowledgment by leadership that a greater focus on this issue needs to occur. The interactive closing plenary a couple of years ago that demonstrated cyber hacking of control equipment highlighted this issue for attendees. Many of the Department of Energy's (DoE) National Nuclear Security Administration laboratories have growing initiatives in this area, and it is important for the Institute to stay current on how they will impact all of the Technical Divisions.

As a result of the growing threat by both state and nonstate actors, the United States has named both space and cyberspace as "warfighting domains," raising the level of importance in the defense posture for both of these new areas. Some literature has suggested that cyberattacks could represent a next-generation weapon of mass destruction,[7] whereas others reflect on language in the U.S. Nuclear Posture Review that nuclear weapons could be used in response to a significant cyberattack.[8] DoE Secretary Rick Perry has launched a new initiative to establish a special cyber program and an Assistant Secretary for Cyber and Infrastructure Protection, and the Pentagon has stood up CYBERCOM as a Unified Combatant Command. A new National Institute of Standards and Technology (NIST) cybersecurity control compliance requirement is now in all Department of Defense (DoD) contracts and subcontracts and will be audited in 2019. Note that the DoD-led initiative to require certification of contractor and subcontractor information technology (IT) systems in alignment with NIST 800-171 Rev.1 is a harbinger of what other national security agencies (such as the DoE) might eventually require. The 100+ security controls required by that standard have the potential to further impact the IT environments that are so critical to the work being done in the Institute's areas of competency.

Connecting Policy and Technical Communities to Develop Solutions

As the Institute has focused more on this issue, a natural path toward better engagement in our Technical Divisions has occurred. The experiment during the upcoming 60th Annual Meeting to have a plenary speaker each day will provide the opportunity for enhancing this linkage, as will efforts to more formally engage with policy organizations from the Nuclear Threat Initiative to Carnegie, as well as international collaborations with organizations such as the European Safeguards Research and Development Association and the World Institute for Nuclear Security.

Artificial Intelligence and Machine Learning

AI and the increasing use of technology in every aspect of our world has captured the imagination of the next generation and created new opportunities and challenges. With the intermingling of hypersonic delivery weapons adopted by Russia and China, the whole landscape of nuclear deterrence may change. Instead of having the luxury of 30 minutes or more to make a decision for a nuclear retaliation launch, leaders may instead be faced with having to make a decision in a matter of minutes — leading to the potential for AI systems to play a larger role.[9]

Outreach to the Nuclear Industry

That this issue was identified as a priority demonstrates why the Facilities Operations Division was formed, and why the EC has developed a fuel cycle graphic that shows how each Technical Division is engaged in activities associated with every aspect of the nuclear fuel cycle. The Institute's low-profile approach to publicly responding to policy issues contributes somewhat to this lack of engagement, but perhaps the marketing expertise of our new management company, Association Headquarters, may be of assistance in addressing this issue.

During the next year, the EC and Strategic Planning Committee will continue to analyze and develop the feedback provided by our membership during the 2018 closing plenary, while evaluating the dramatic changes in our world with respect to the nuclear environment, with the hope of creating a broadly supported set of strategic initiatives that will benefit our membership.

This column is intended to serve as a forum to present and discuss current strategic issues impacting the Institute of Nuclear Materials Management in the furtherance of its mission. The views expressed by the author are not necessarily endorsed by the Institute, but are intended to stimulate and encourage JNMM *readers to actively participate in strategic discussions. Please provide your thoughts and ideas to the Institute's leadership on these and other issues of importance. With your feedback, we hope to create an environment of open dialogue, addressing the critical uncertainties that lie ahead for the world, and identify the possible paths to the future based on those uncertainties that can be influenced by the Institute. Jack Jekowski can be contacted at jpjekowski@aol.com.*

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2. Seven questions were provided to the panelists prior to the closing plenary, with several multiple-choice answers, including "other." The panelists and attendees were then queried for more details. The questions posed were the following: (1) What is the current top global challenge/risk/threat with respect to nuclear proliferation? (2) What is the current top global challenge/risk/threat with respect to nuclear security? (3) Which risk set concerns you more? (4) What are the greatest cyber threats related to nuclear materials management? (5) What are the top three areas INMM should focus on? (6) Which technology has the best chance to become a "game changer" (plus or minus) for INMM? (7) Where should INMM increase its attention?
3. Panelists included Dr. Jacques Baute, director, Division of Information Management, Department of Safeguards, International Atomic Energy Agency; Dr. Bassam Abdullah Khuwaileh, assistant professor, Nuclear Engineering Program, University of Sharjah; Mitsuo Koizumi, manager, Technology Development Promotion Office, Integrated Support Center for Nuclear Nonproliferation and Nuclear Security, Japan Energy Atomic Agency; Sonia Fernández Moreno, planning and evaluation officer, Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials; and Julie Oddou, head of the Committee Technique Euratom, Atomic Energy Commission.
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Calendar

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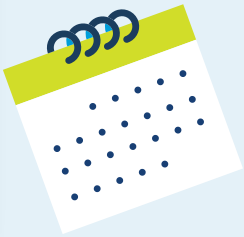

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Speakers

THERESE RENIS

Therese Renis serves as the Director of Division of Concepts and Planning in the Department of Safeguards of the International Atomic Energy Agency (IAEA). Her division is responsible for strategic planning, the development and promotion of safeguards concepts and policy, the coordination of research and development activities, the implementation of the quality management system of the Department, and the development and provision of training. Areas of focus have included the development of safeguards concepts and approaches, implementation of safeguards strengthening measures, including implementation of measures of the model additional protocol and State evaluation; and most recently on the furthering the IAEA's implementation of safeguards for each State as a whole. She has served in the Safeguards Department since 1991, including as a safeguards inspector and Operation Section Head with a focus on safeguarding spent fuel reprocessing plants; advisor to the Deputy Director General -- Head of the Department of Safeguards; and as head of the Section for the development of safeguards concepts and approaches.

TAMMY TAYLOR

Tammy Taylor has served as the Director of the International Data Centre (IDC) Division of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) since August 2018. Before joining the CTBTO, Taylor served as the Chief Operating Officer of the National Security Directorate at the Pacific Northwest National Laboratory (PNNL) where she led the mission execution, capability development, and project management of the directorate of three divisions and four project management offices representing more than 1,300 national security staff. Prior to joining PNNL in 2013, Tammy served in a number of positions over fifteen years at Los Alamos National Laboratory (LANL). She served in positions as the Deputy Associate Director of Chemistry, Life and Earth Sciences, the Division Leader of Nuclear Engineering and Nonproliferation, a group leader, project leader, staff member and Director's Postdoctoral Research Fellow. From early 2007 to mid-2010 she was an Intergovernmental Personnel Act assignee from LANL in the Office of Science and Technology Policy (OSTP) in the Executive Office of the President. She managed the national science and technology portfolio on nuclear defence issues within the National Security and International Affairs Directorate of OSTP for Dr. John Holdren and Dr. Jack Marburger, Science Advisors to President Obama and President Bush, respectively. Tammy has a Master's of Science and Doctorate of Philosophy in Environmental Engineering from the Georgia Institute of Technology. Her undergraduate degree in Civil Engineering is from New Mexico State University.

STEPHAN LECHNER

Dr Stephan Lechner, based in Luxembourg, is Director of Euratom Safeguards and co-ordinator for cyber security policy in the Directorate General for Energy of the European Commission. Before this appointment to this position in July 2016, he was Director of the Institute for the Protection and the Security of the Citizen at the European Commission's Joint Research Centre in Italy for more than eight years. Before joining the European Commission in 2007, he was International Department Head and Senior Manager at Siemens Corporate Technology in Munich. Between 1989 and 2007, Dr Lechner spent more than 18 years in the hi-tech sector of private industries where he held various management positions both in operations and in industry research. Dr Lechner holds a degree in mathematics and computer sciences from Giessen University, Germany, and a doctoral degree in cryptography from Linz University, Austria. Dr Lechner is certified information systems security professional (CISSP) according to international standards.