Design and validation of inert homemade explosive simulants for X-ray-based inspection systems

Anthony A. Faust*[a], Sabatino Nacson[b,c], Bruce Koffler[b,d], Éric Bourbeau[e], Louis Gagne[a], Robin Laing[a], C. John Anderson[a]

[a] Defence Research and Development Canada, Suffield Research Centre, PO Box 4000 Station Main, Medicine Hat, AB, T1A 8K6, Canada;
[b] Visiontec Systems, 8-6790 Kitimat Rd., Mississauga, ON, L5N 5L9, Canada;
[c] TeknoScan Systems Inc., Vaughan, East 50A Caldari Rd., ON, L4K 4N8, Canada;
[d] SecureSearch Inc., 91175-2901 Bayview Ave., North York, ON, M2K 2Y6, Canada;
[e] Optosecurity, 420-1280 Boulevard Lebourgneuf, Quebec City, QC, G2K 0H1,Canada

ABSTRACT

Transport Canada (TC), the Canadian Armed Forces, and other public security agencies have an interest in the assessment of the potential utility of advanced explosives detection technologies to aid in the detection and interdiction of commercial grade, military grade, and homemade or improvised explosives (HME or IE). The availability of suitable, non-hazardous, non-toxic, explosive simulants is of concern when assessing the potential utility of such detection systems. Lack of simulants limits the training opportunities, and ultimately the detection probability, of security personnel using these systems. While simulants for commercial and military grade explosives are available for a wide variety of detection technologies, the design and production of materials to simulate improvised explosives has not kept pace with this emerging threat. With the support of TC, Defence Research and Development Canada (DRDC), Visiontec Systems, and Optosecurity engaged in an effort to develop inert, non-toxic X-ray interrogation simulants for IE materials such as ammonium nitrate, potassium chlorate, and triacetone triperoxide. These simulants were designed to mimic key X-ray interrogation-relevant material properties of real improvised explosives, principally their bulk density and effective atomic number. Different forms of the simulants were produced and tested, simulating the different explosive threat formulations that could be encountered by front line security workers. These simulants comply with safety and stability requirements, and as best as possible match form and homogeneity. This paper outlines the research program, simulant design, and validation.

Keywords: Homemade explosives, Improvised explosives, X-ray, simulant

1. INTRODUCTION

Transport Canada (TC), the Canadian Armed Forces (CAF), and other public security agencies have an interest in the assessment of the potential utility of advanced explosives detection technologies to aid in the detection and interdiction of commercial grade, military grade and homemade, or improvised, explosives (IE). The availability of suitable, non-hazardous, non-toxic, explosive simulants is of concern when assessing the potential utility of such detection systems; lack of simulants limits the training opportunities, and ultimately the detection probability, of security personnel using systems in the field.

While simulants for commercial and military grade explosives are available for a wide variety of detection technologies (such as vapor detectors, trace particulate detectors, neutron and X-ray-based bulk inspections systems), the design and production of materials to simulate improvised explosives has not kept pace with this emerging threat.

Defence Research and Development Canada, Suffield Research Centre (DRDC) is able to produce small quantities of improvised explosives as required to aide investigators and first responder organizations to conduct rapid, evidence-based assessments of many IE formulations, compositions, and recipes. In support of TC objectives, the authors took

* Corresponding author: Anthony.Faust@drdc-rddc.gc.ca, Tel +1 403 544 4011 ex. 5352, Fax +1 403 544 4704

this opportunity to measure the X-ray relevant physical parameters of a number of IE formulations in order to create explosive simulants for use in assessment of, and training on, X-ray-based inspection systems.
The important observation concerning improvised explosives is that they are, of course, improvised and thus could present very differently to security operators depending on their exact formulation. The principal intent, therefore, of this first effort to engage industrial partners was not simply to design simulant formulations for a single IE example but rather to design a simulant development process, by which new IE formulations could be manufactured and assessed at DRDC facilities, with the resulting X-ray relevant parameterization being made quickly available to our industrial partners for rapid prototyping of new training simulants for subsequent deployment to interested end-users. This capability is now in place.

1.1 X-ray Image Analysis in Security Applications

The value of X-ray interrogation of luggage and containers is well known to the public security community. In scenarios where this technology can be utilized effectively it is a cornerstone of the modern security apparatus.

The principal idea behind these "X-ray in – X-ray out" techniques is to irradiate a suspicious object or area with an X-ray flux and measure the reflected or transmitted radiation. For photon energies of interest ($E\gamma < 120$ keV, typically available through electronic X-ray generators), the primary physical interactions with the target materials are: coherent scattering, the photoelectric effect, and Compton scattering [1,2]. Fortunately, these interactions and their relative contributions to the detection performance of an X-ray-based technology can be described in terms of easily measured physical quantities: the incident photon energy, $E\gamma$, the mass density, ρ, and average atomic number, Z_{eff}, of the target. As Z_{eff} is largely independent of $E\gamma$ in the energy range used in common aviation security X-ray systems [3], simulants can therefore be created by matching the measured (ρ, Z_{eff}) of the target material.

The attenuation is related to the intervening materials in a linear fashion. That is, if μ_i is the *linear attenuation coefficient*, and ρ_i the density, of the i^{th} element in the compound, Bragg's rule can be applied to in order to calculate the mass attenuation coefficient of a compound by summing μ/ρ for each of the constituent elements weighted by ω_i, the weight fraction of the i^{th} element in the compound, $\mu/\rho = \sum_{i=1}^{n} \omega_i (\mu_i/\rho_i)$. For pure elemental materials, μ is a function of the atomic number, Z, $\mu(Z)$, however for compound materials, as are most materials one would practically deal with, intermolecular bonds make defining Z for a compound difficult. Instead, the average atomic number, Z_{eff}, is used. As Z_{eff} depends solely on the elemental composition and, as noted, is essentially $E\gamma$ for the energy range of interest, the bulk mass attenuation coefficient of a compound is $\mu(Z_{eff})/\rho$.

Unfortunately, without prior knowledge of the constituents of a volume under interrogation, a single X-ray energy can only determine an overall μ/ρ. This application of X-ray interrogation would be familiar to the reader as traditional grey-scale X-ray imaging, which was first developed using film-based systems but is still in wide use today via electronic detectors. In this approach, the system generates a visual representation of the *attenuation* of the incident X-ray flux. That is, the absorption or scattering of X-rays the material properties of the target. For example, highly attenuating materials such as metals traditionally appear white, while less attenuating materials such as air appear black. In a security context, these interrogation systems were used for anomaly detection; allowing the operator to detect illicit materials by shape, size, and contrast [4] - such as a metal knife hidden in a suitcase - but were limited in their ability to identify other threat materials.

Modern inspection systems, however, utilize a dual energy approach. Comparing the attenuation at two energies, $\mu(E_1, Z_{eff})$ and $\mu(E_2, Z_{eff})$, it is possible to solve for both ρ and Z_{eff} of the target [5]. Dual energy X-ray systems, therefore, allow for (ρ, Z_{eff}) material classification [6]. In practice, single view images make accurate determination of ρ difficult. Instead, to aide an operator in detection, a false color image can be made to classify materials based on Z_{eff}; traditionally orange for organic with $Z_{eff} < 10$, green for inorganic with $10 < Z_{eff} < 20$, and blue for metallic materials with $Z_{eff} > 20$. This level of discrimination is known to enhance the ability of security operators to identify threat materials in screening operations. Commercially available X-ray systems often incorporate automated alarm algorithms that depend primarily on this determination of Z_{eff}. Consequently, for the simulants to be valid for testing this equipment, they must match the effective atomic number of the real explosives better than ±3.5% of the targeted effective atomic number of each explosive type [7].

While a great advance in detection efficiency, simple dual energy X-ray systems are unable to unfold the contributions from overlapping materials in the target volume, yielding a weighted average result for each beam path and allowing for the possibility of false negatives. Additional improvements to the dual energy approach, including multi-view or even volumetric computed tomography (CT) [8], allow for the separation of overlapping materials within the inspection volume, and therefore more accurate determination of (ρ, Z_{eff}) for these sub-volumes (voxels) . This enables improved performance of automatic explosive detection algorithms, superior visualization to assist operator interpretation, and automatic visual cueing for on-screen threat resolution.

It is clear that to fully exploit the capabilities of current and emerging X-ray inspection technology, it is important that the simulant formulations proposed be, as best as possible, homogeneous mixtures with the correct (ρ, Z_{eff}) . Inhomogeneous mixtures would simply not image correctly at the voxel-analysis level of emerging 3D-capable systems.

In a comprehensive review of X-ray explosives detection techniques for checked baggage, the density and effective atomic number for various explosives and non-explosive materials has been reported [9]. For reference, a subset of this data is reproduced in Table 1 below, where the materials are either explosives, explosive precursors, or fuels commonly associated with IE formulations.

Table 1. Selection of commercial and improvised explosives, precursors, and other common materials, presented with their X-ray relevant parameters: the effective atomic number, and density, from [9].

Name	Nature	Z_{eff}	ρ [g/cm^3]
RDX	Explosive	7.2	1.8
TNT	Explosive	7.1	1.7
TATP (dimer)	Explosive	6.7	0.7
Nitromethane	Explosive	7.2	1.1
Ammonium Nitrate	Precursor	7.4	1.8
H2O2	Precursor	7.7	1.5
Urea	Precursor	7.4	1.3
Uric acid	Precursor	6.9	1.9

Name	Nature	Z_{eff}	ρ [g/cm^3]
H2O	Water	7.4	1.0
Fructose	Sugar	7.0	1.5
Saccharose	Sugar	6.9	1.6
Sorbitol	Sugar	6.9	1.5
Polyethylene	Polymer	5.5	0.9

1.2 Threat Characterization

Explosive threats presented to security operators have long been based on military and commercial grade explosives, however IE threats have become more prevalent as the security threat against civil aviation shifted from hijacking in the 1980s towards deliberate terrorist attacks in the 1990s [9].

Of the myriad IE formulations possible, TC requested that the initial simulant design effort should focused on the fundamental constituent materials that represent a large fraction of the IE threat today. These were identified as ammonium nitrate (AN), potassium chlorate (KCl03), and triacetone triperoxide (TATP).

In the subsequent discussion, the reader will understand that the authors felt it prudent to omit specific details of the explosive formulations or explosive yields. While much of this information is available to the interested reader in open sources, there is no perceived benefit, nor need, to relay that level of detail. It was felt sufficient to note what materials are of concern, and discuss their X-ray-relevant parameters.

1.3 Ammonium Nitrate

Ammonium nitrate (AN) is a commonly available fertilizer. Commercial AN is often supplied in *prill* form; small beads of AN often coated with a thin layer of anti-caking agent. AN is not itself an explosive, and must be mixed with a fuel [10]. When mixed with fuels, such as diesel or kerosene, it has a long history of use in explosive mixtures used in civil engineering and mining applications. Because of the ease of access to large quantities of AN, it has found use by

insurgents in Iraq and Afghanistan, as well as domestically, such as the Oklahoma City bombing in 1996 or the planned (and thwarted) attack in Canada by the "Toronto 18".

The simulants developed in this effort were based on representative AN-based explosive mixtures produced by DRDC. Two common AN-based explosives considered in this study were ammonium nitrate and fuel oil (ANFO), and ammonium nitrate and aluminum powder (ANAL). When mixed with fuel oil, ANFO often takes on a pink/orange hue (depending on the color of the dye mixed in with the fuel oil), whereas aluminum mixtures appear metallic grey. These features were captured in the subsequent simulant designs. The variable size and coating of the AN prills available from manufacturers,, as well as the ratio of added fuels (including metal powders) all conspire to present AN threats with a range of densities and Z_{eff}, one value of which is presented in Table 1.

1.4 Potassium Chlorate

Potassium chlorate (KClO3, referred to as PC below) is the most commonly used, and thus available, chlorates in industry, and is one of the few IE constituents besides AN that is readily available in bulk (although it is noted that several countries now restrict the purchase of AN and PC). Its use has been recommended in "do-it-yourself" literature for small anti-personnel devices, while the terrorists in Bali on October 2002 demonstrated its potential in large devices. Chlorates, like other inorganic salts, have a very low vapour pressure, which poses a challenge to detection techniques that rely on vapour sniffing. It presents as a white crystalline powder in its raw form.

Commercial sources report densities in the range of 2.32 - 2.34 g/cm3. However, when measured for this investigation, a commercial sample of the same substance was found to have a density of 1.58 g/cm3. This is likely due to the fact that the measurement was done using crystals, not in a bulk form, and the crystals were stacked and not compressed, leaving air spaces between them. This range of variation in density with formulation technique is common with IEs, and will pose a challenge to automated detection algorithms.

1.5 Triacetone Triperoxide

The peroxide explosives triacetone triperoxide (TATP) and hexamethylene triperoxide diamine (HMTD) have become popular with terrorists because they are easily prepared from readily obtainable ingredients, although the synthesis is fraught with danger. Although TATP and HMTD do not contain any of the traditional oxidizer salts, such as NO_x or ClO_x in AN and PC above, the O-O bond in the peroxide is a source of oxygen available for potentially rapid self-oxidation and explosion. Both TATP and HMTD are classed as primary explosives. For example, Richard Reid, the airline "shoe bomber," used TATP as part of his firing mechanism in the attempted bombing of a US airliner in December, 2001. The reported values of (ρ, Z_{eff}), particularly ρ, vary significantly with source, as seen in Table 2.

Table 2 Peroxides densities and effective atomic numbers.

Explosive	**Formula**	$\mathbf{Z_{eff}}$ (Calculated)	$\mathbf{Z_{eff}}$ [9]	ρ **[g/cm^3]**		
TATP	$C_9H_{18}O_6$	6.549	6.7	1.2 [11]	0.7 [9]	0.54 (DRDC sample)

2. SIMULANT DESIGN

DRDC is currently producing small quantities of improvised explosives, on-demand, as part of a national strategy to help investigators and first responder organizations to obtain rapid, evidence-based threat assessments of many IE formulations, compositions, and recipes.

Using these IE samples, dual energy X-ray images were taken of pure targets using a Smith's HS6046si[1] dual-energy X-ray interrogation system, along with calibration phantoms. The raw data from these images were collected using an in-

[1] http://www.smithsdetection.com/en/security-checkpoint-solutions/62-security-checkpoint-solutions/hi-scan-6046si.html

line data collection module designed by Optosecurity, who then analyzed these images in order to generate (ρ, Z_{eff}) values for each formulation using a procedure described below. Visiontec used these measured values as a target for simulant design.

The IE simulants were designed by carefully selecting the composition and amount of the material components based on their measured mass densities, their grain sizes, and their contribution to the theoretical effective atomic number of the final composition. Fortunately, many of the fuels and binders added to energetic salts to produce IEs are themselves benign, such as oils, sugars, and plastic, and so they can form part of the simulant formulation, which adds another layer of realism.

A further constraint was to limit the simulant materials used to manufacture the simulants to those materials that are safe and non-toxic. Some simulants, such as the Non-Hazardous Explosives for Security Training and Testing (NESTT) materials designed for canine testing, incorporate actual explosive material [12] along with other fillers. This can cause inspection systems to report misleading information, confusing an operator or compromising a detection performance test. Because of their mismatch (ρ, Z_{eff}) and potential for contamination, such simulants would have limited usefulness for training operators, testing automated X-ray detection systems, and accurately simulating improvised explosives. Thus all base materials considered were to be non-hazardous, non-toxic, and stable under expected operating conditions.

Examples of components and binders for making stimulants include boron carbide, carbon, aluminum, industrial oils, organic wax, organic acids, dioctyl adipate, estane, ethylene vinyl acetate, polyisobutylene, polyethylene, and metal oxides such as silica, ferric oxide and alumina. Organic compounds similar in physical characteristic to the target material include urea and/or alkyl ureas such as dimethyl or ethyl urea, nitroarene and diphenyl urea. This list is by no means exhaustive; any organic or inorganic components that can achieve the desired mass density and effective atomic number could be used.

To test candidate simulant formulations, it was efficient to first estimate the resulting Z_{eff} using one of the analytical models available [7]. In general, these models assume that the simulant materials consist of a mixture of elements or compounds. Figure 1 presents a typical simulation, in this case of pure potassium chlorate based on chemical supplier density information.

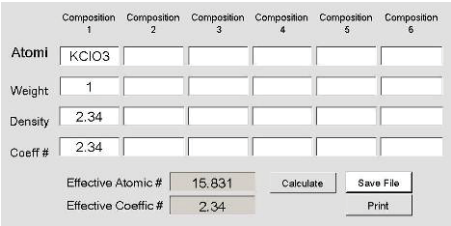

Figure 1. Simulation of pure Potassium Chlorate effective atomic number.

3. VALIDATION

Validation of the simulant formulations is a critical requirement in the development process. The authors utilized two analysis procedures, both to simplify logistics and sample handling between distant laboratories, and as a means to ensure consistency of results.

3.1 Optosecurity

Analysis used images of both threat materials and simulants collected at DRDC Suffield using a Smith's HS6046si[2] X-ray Interrogation System, which was modified by the addition of a custom data collection unit designed by Optosecurity

[2] http://www.smithsdetection.com/en/security-checkpoint-solutions/62-security-checkpoint-solutions/hi-scan-6046si.html

in order to capture the raw data necessary to perform subsequent data analysis. The images were then transferred electronically to Optosecurity's facility in Quebec City for further analysis.

Optosecurity had previously developed a method to accurately determine the X-ray-relevant properties of a substance as part of its R&D effort for the development of its liquid threat detection solution. Although the theory behind converting X-ray raw data into mass density and average atomic number has been known for a number of years, the specific methodology invented by Optosecurity relies heavily on 3D modeling and X-ray simulation [13, 14]. This methodology provides very accurate and repeatable results, especially when the substance under analysis is homogenous and contained in a well-defined and geometrically simple container, such as a typical laboratory bottle.

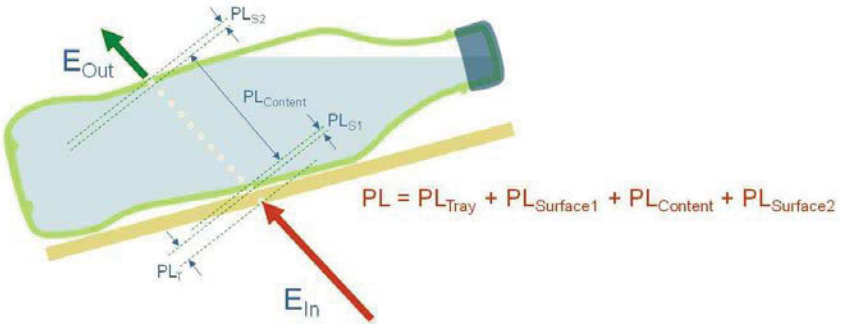

Figure 2. Physical dimensions used in Optosecurity's simulation-based data analysis algorithm. © Optosecurity.

In order to estimate the mass density and Z_{eff} of a given compound using X-ray raw data, one must first compute the optical path for every layer that the photons go through for any given pixel, such as demonstrated in Figure 2 above. To do this, a container is filled with the target substance and placed into a custom sample tray. This yields an X-ray image, as shown in Figure 3.

Figure 3. Custom sample tray with target sample, used during data collection on the Smith HS6046si.

Figure 4. Computer rendering of sample tray, used during the iterative, simulation-based data analysis. © Optosecurity

From this X-ray image, the software determines the position of the tray in 3D space, finds the container in the image, and determines its properties in terms of length, width and cross section to also position it in 3D space. Using this information, the software then reconstructs a complete 3D model of the scene, including the pre-defined sample tray.
With this 3D model, an X-ray simulation is conducted that is used to predict with great accuracy the output signal intensity of the system, as a function of path length and material nature. These simulations vary (ρ, Z_{eff}) of the substance under evaluation, comparing the predicted X-ray image against the real image until a match is made within the required tolerance.

Using this method, the mass density measurements have been found to be relatively stable. Disparities observed between the theoretical values and the measured values could in part be due to errors in the volume estimation taken when the explosive samples were packaged. The high Z_{eff} material measurements were slightly less stable since they contain high atomic mass compounds. The consequence is that a small difference between the theoretical mass ratios and

the real one or any heterogeneity in the mix can introduce a significant variation in the computed Z_{eff}. This sensitivity to high Z constituents of compound materials is a known feature of X-ray-based analysis, as mentioned previously.

The Optosecurity method was used to determine the target (ρ, Z_{eff}) of the pure IE samples manufactured at DRDC Suffield, and, during the early development of the AN simulants, as a cross-check of candidate simulants fabricated by Visiontec.

3.2 Visiontec

As the simulant candidates were fabricated at Visiontec, they used a VOTI XR3D-6[3] X-ray imaging system to conduct on-site analysis of the candidate formulations.

The instrument has the ability to estimate Z_{eff} for an area of the image selected by the operator. The operator, zooming on various areas of the sample, recorded the reported Z_{eff} values. These measurements were found to have a systematic 2% accuracy when calibrated against known materials covering a range of effective atomic numbers from 6.5 to 26. Multiple measurements were taken from each image in order to reduce statistical errors, and added in quadrature to the systematic error.

The XR3D-6 scanner incorporates a single X-ray source, which does not permit direct measurement of density of the material. Therefore, the density was estimated by direct mass to volume calculations, which was at times confounded by the material form (especially the powders).

4. RESULTS

4.1 Ammonium Nitrate, ANFO, and ANAL

Figure 5 below depicts the physical form of actual AN and ANFO samples that served as reference samples for the creation of a number of AN, ANFO, and ANAL simulants, themselves shown in Figures 6-8.

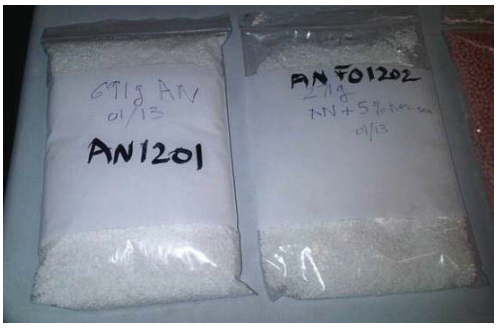

Figure 5. Ammonium Nitrate (AN) prill (sample AN1201), and AN prill plus kerosene (ANFO) (sample ANFO1202).

Figure 6. From the left, AN simulants 1301 and 1302, and ANAL simulant 1303.

[3] http://www.votigroup.com/products/600-class/xr3d-6/

Figure 7. From the left, ANAL simulants 1304 and 1305

Figure 8. ANAL simulants with different prill sizes.

The following tables related the calculated and measured X-ray relevant parameters for the reference samples, in Table 3, and a selection of the resulting ANFO, and ANAL simulants in Table 4.

Table 3. Calculated and measured X-ray relevant parameters for the AN and ANFO reference samples.

Sample	**AN1201 (Reference)** AN prill fertilizer grade	**ANFO1202 (Reference)** AN prill soaked in Kerosene
Calculated Z_{eff}	7.40	7.40
Measured Z_{eff} Visiontec Optosecurity	 7.05 ± 3.0% 7.30 ± 0.4%	 6.87 ± 2.4% 7.39 ± 0.9%
Density [g/cm^3] Visiontec Optosecurity	 0.85 1.04 ± 1%	 0.80 1.02 ± 1%
VOTI Image		
Description	Prill size 1.4-2 mm	Prill Size 1.4-2 mm

Table 4. Calculated and measured X-ray relevant parameters for the AN-based simulant formulations.

Sample	**AN01301** Simulated ANFO	**AN01302** Simulated ANAL	**AN01303** Simulated ANFO	**AN01304** Simulated ANAL	**AN01305** Simulated ANAL
Calculated Z_{eff}	7.10	7.22	7.47	7.36	7.39
Measured Z_{eff} Visiontec Optosecurity	 6.78 ± 2.4% 7.02 ± 0.3%	 6.88 ± 2.5% 7.03 ± 0.3%	 6.74 ± 2.6% 6.81 ± 0.1%	 6.85 ± 2.2% 7.04 ± 0.1%	 6.91 ± 2.2% 7.20 ± 0.1%
Density [g/cm^3] Visiontec Optosecurity	 0.65 0.694 ± 1%	 0.66 0.599 ± 0.5%	 0.66 0.593 ± 0.2%	 0.62 0.600 ± 1%	 0.71 0.708 ± 0.1%
VOTI Image					
Description Prill size	3-4 mm	3-4 mm	2-6 mm	3-4 mm	2-5 mm

4.2 Potassium Chlorate

Figure 9. Commercial PC Sample.

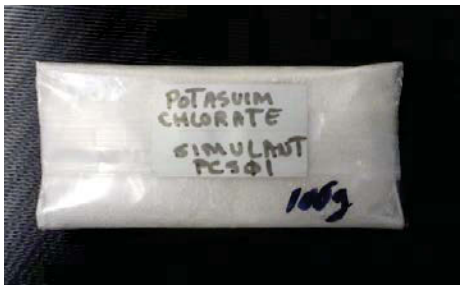

Figure 10. PC simulant.

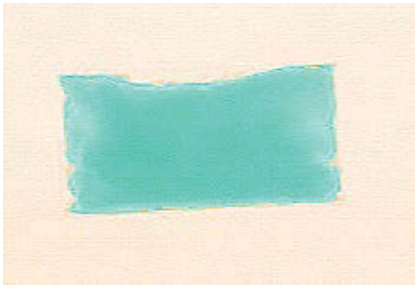

Figure 11. Potassium chlorate
Z_{eff}= 14.93 ± 3.9%

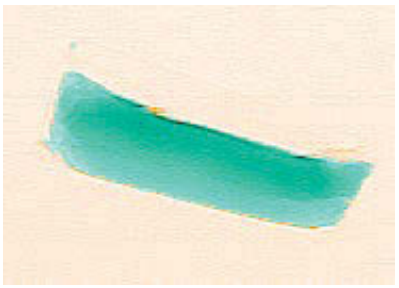

Figure 12. PC simulant
Z_{eff}= 14.51 ± 3.4%

Figures 9 and 10 above depict the physical form of a commercial sample of PC used as a reference target, along with a PC simulant produced in this study. Figures 11 and 12 present the associated VOTI XR3D-6 images of the same, along with their measured Z_{eff} values. The standard deviation of the measurements indicates the variation between different areas of the sample. If the sample is homogenously blended, a small relative standard deviation would be observed and usually is less than 10% for a good homogenous sample. The consistent difference between calculated Z_{eff} and measured Z_{eff}, for both real and simulant PC, may be related to the sensitivity of the Z_{eff} calculations to high Z components.

Table 5. Comparison of material characteristics between actual and simulant PC samples.

Characteristic	**Real PC**	**PC Simulant**	**Difference**
Colour	White	White	
Texture	Smooth	Smooth	
Density [g/cm^3]	1.53	1.58	3%
Effective Atomic Number (calculated)	15.83	15.82	0.1%
Effective Atomic Number by X-Ray	14.9 ± 3.9%	14.5 ± 3.4%	2%
Color in X-Ray Image	Green	Green	

All components in the PC simulant demonstrated stability over three months of use in a zip-lock plastic bag. Blended mixtures of PC simulant were subjected to elevated oven temperature of 55 C for 15 hour incubation with no adverse effect on sample integrity or characteristics. The same mixture kept in a fridge at a temperature of 4 C was stable and did not separate. Water absorption was also minimized when appropriately wrapped and packed in a plastic bag.

4.3 TATP

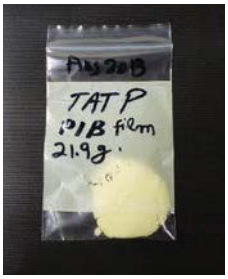

Figure 13. Real TATP sample in polyisobutylene matrix.

Figure 14.TATP simulant in polyisobutylene matrix.

Figure 15. TATP simulant in crystal form.

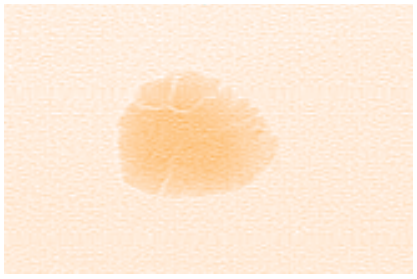

Figure 16. TATP in polyisobutylene matrix Z_{eff}= 6.46 ± 2.8%

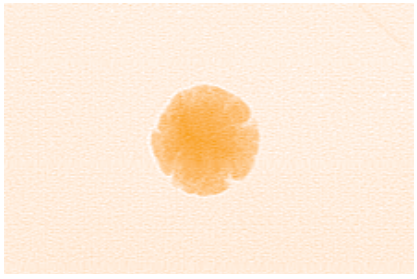

Figure 17. Simulant TATP in polyisobutylene matrix Z_{eff}= 6.48 ± 2.2%

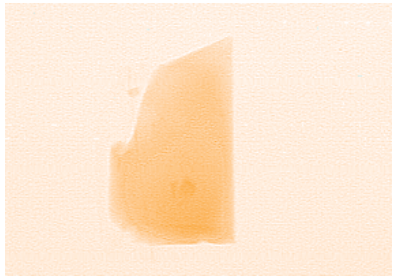

Figure 18. Simulant TATP in crystal form Z_{eff}= 6.46 ± 3.0%

Figure 13 above depicts the physical form of a sample of TATP, stabilized in an polyisobutylene matrix, which was used as a reference target in this study. Figures 14-15 are the resulting simulants produced in this study; one in a similar

polyisobutylene matrix, and one depicting the crystal form of TATP. Figures 16-18 present the associated VOTI XR3D-6 images of the stabilized TATP sample and resulting simulants, along with their measured Z_{eff} values.

Table 6. Comparison of material characteristics between actual and simulant TATP samples.

Characteristic	**Real TATP Powder**	**TATP Simulant Powder**	**Difference**
Colour	White	White	
Texture	Smooth	Smooth	
Density (measured) [g/cm^3]	0.42	0.48	14%
Effective Atomic Number by X-Ray	6.7 ± 2.3%	6.46 ± 3.0%	3.6%
Colour in the X-Ray image	Orange	Orange	

Table 7. Comparison of material characteristics between actual and simulant TATP samples, in poly-isobutylene matrix.

Characteristic	**Real TATP in Polymer**	**TATP Simulant in Polymer**	**Difference**
Colour	White (Tint of yellow)	White	
Texture	Smooth	Smooth	
Density (measured) [g/cm^3]	0.45	0.50	11%
Effective Atomic Number by X-Ray	6.46 ± 2.8%	6.48 ± 2.2%	0.3%
Colour in X-Ray Image	Orange	Orange	

5. CONCLUSION

This paper discussed the development of inert, non-toxic X-ray-relevant simulants for IE materials such as ammonium nitrate (AN) and its products ANFO and ANAL, potassium chlorate (PC), and triacetone triperoxide (TATP). These simulants were designed to mimic key X-ray interrogation-relevant material properties of improvised explosives, principally their density and effective atomic number.

Different forms of the simulants were produced and tested, simulating the different explosive threat formulations that could be encountered by front line security workers. The simulants were found to have appropriate density and effective atomic number to be rendered appropriately in Z_{eff}-based false colour imaging used in two commercially available X-ray interrogation systems. Further validation tests on multi-beam and 3D CT imaging systems using automatic target detection algorithms are needed.

Importantly, the authors validated a simulant development process by which new IE formulations can be manufactured and assessed at DRDC facilities, with the resulting X-ray relevant parameterization being made quickly available to our industrial partners for rapid prototyping of new training simulants for subsequent deployment to interested end-users.

AKNOWLEDGEMENTS

This project was initiated and supported throughout by Mr Al Manii, Senior Development Officer, Transport Canada, Transport Canada (Transportation Development Centre). The project was lead and managed by DRDC. Funding for the project was provided by TC and the DRDC Centre for Security Science (CSS) under Public Works and Government Services Canada (PWGSC) contracts W7702-125332/001/EDM and W7702-125427/001/EDM. TC also provided significant in-kind support including the X-ray systems, data capture equipment, facility development, and associated training. The authors would like to thank Ms Colleen Rodi, President/Owner, Visiontec Systems, Ontario, for her support.

REFERENCES

[1] Dyson, N.A., [X-rays in Atomic and Nuclear Physics, 2 ed.], Cambridge University Press, Cambridge UK (1990). ISBN: 0 521 26280 1.

[2] Knoll, G.F., [Radiation Detection and Measurement, 3 ed.], New York, NY: John Wiley & Sons (2000). ISBN 0 471 07338 5.

[3] Spanier, L.J., and Kury, J.W., "Design and validation of inert bulk energetic material simulants for field testing X-ray based inspection systems," in Proc. of the 2nd Explosives Detection Technology Symposium and Aviation Security Technology Conference, pp. 55-59 (1996).

[4] Krug, K., and Stein, J., "Advanced Dual Energy X-ray for Explosives Detection", in Proceedings of the First International Symposium on Explosive Detection Technology, Siraj M. Khan, ed., Atlantic City (1992).

[5] Park, Ji Sung, and Kim, Jong Kyung, "Calculation of Effective Atomic Number and Normal Density Using a Source Weighting Method in a Dual Energy X-ray Inspection System," J. Korean Phys. Soc. 59, p. 2709-2713 (2011). doi: 10.3938/jkps.59.2709

[6] Smiths Detection, "Improving Airport Security, Security-net - the shape of things to come?" Airport International <http://www.airport-int.com/article/securitynet-the-shape-of-things-to-come.html> (2 Apr 2014).

[7] Eilbert, R.F., "Development and evaluation of simulants for x-ray based explosive detection systems," in Proc. of the 2nd Explosives Detection Technology Symposium and Aviation Security Technology Conference, pp. 49-54 (1996).

[8] Ying, Z., Naidu, R., Guilbert, K., Schafer, D., and Crawford, Carl R., "Dual Energy Volumetric X-ray Tomographic Sensor for Luggage Screening," Sensors Applications Symposium, 2007. IEEE SAS '07, p. 1-6 (2007). doi: 10.1109/SAS.2007.374371

[9] Wells, K., and Bradley, D.A., "A review of X-ray explosives detection techniques for checked baggage," Applied Radiation and Isotopes 70(8), p. 1729-1746 (2012). http://dx.doi.org/10.1016/j.apradiso.2012.01.011.

[10] Yeager, K., "Analysis of post-blast residue from a variety of ammonium nitrate based improvised explosives," in 7th Int. Symp. Analysis and Detection of Explosives, 25-28 June 2001, Edinburgh, Scotland, p. 135-152 (2001).

[11] Burks, R.M., and Hage, D.S., "Current trends in the detection of peroxide-based explosives," Analytical and Bioanalytical Chemistry, 395(2), p. 301-313 (2009).

[12] Kury, J.W., and Simpson, R.I., "Development of non-hazardous explosives for security training and testing (NESTT)," Technical Report, Lawrence Livermore National Lab., CA (1995). doi:10.2172/93967

[13] Gudmundson, S., Bourbeau, E., and Perron, L., "Method and system for performing X-ray inspection of a product at a security checkpoint using simulation," Canadian Patent No. CA 2696031. Retrieved from Canadian Patents Database (2010).

[14] Godbout,S., Bourbeau, E., and Gudmundson, S., "Method and apparatus for assessing properties of liquids by using X-rays," Canadian Patent No. CA 2737075. Retrieved from Canadian Patents Database (2011).