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A Comparison of Cargo X-Ray Attenuation as Measured by Top-Down versus Side-View Imaging Systems

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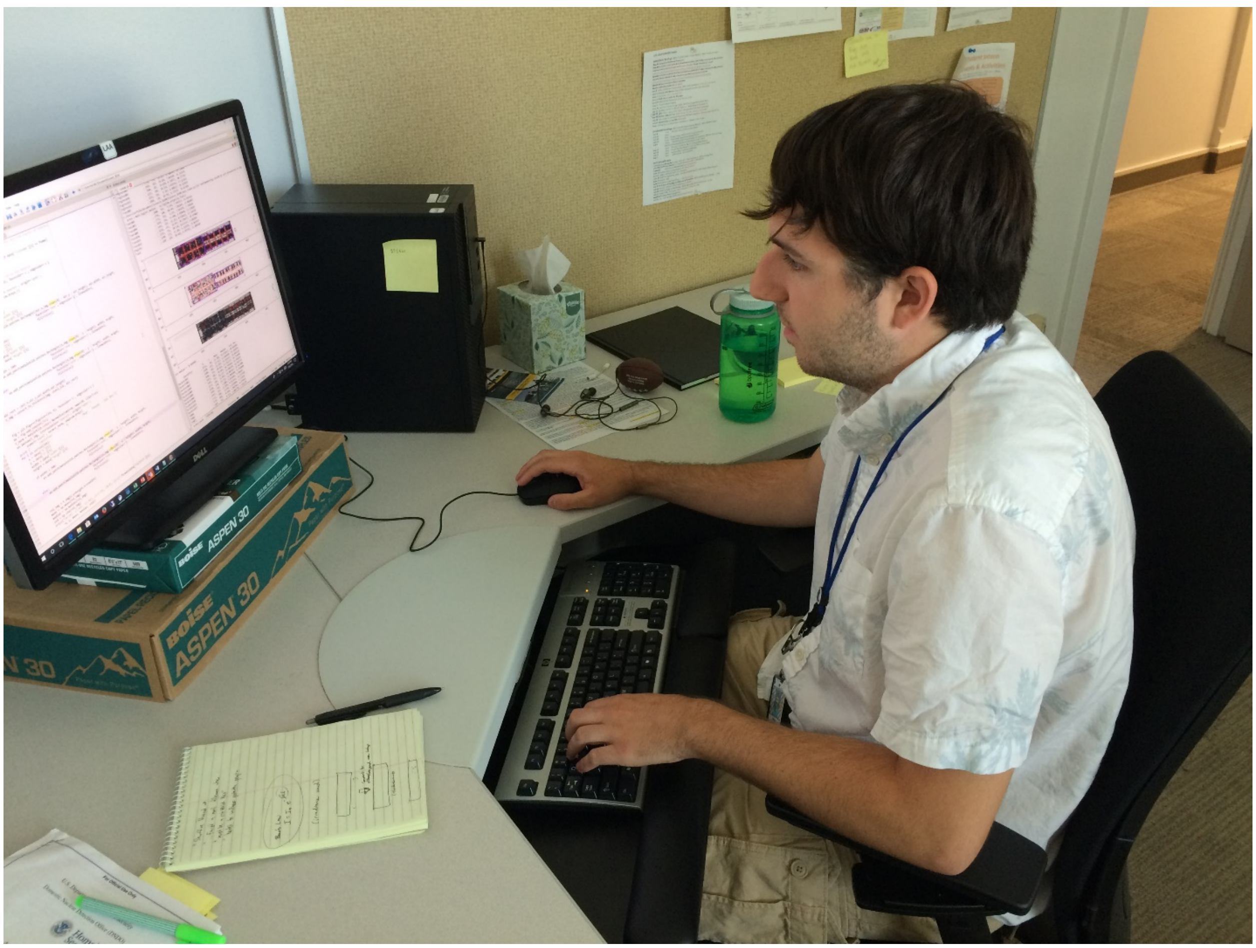
Mentor's Signature: ____

Millions of cargo containers enter the United States every year, each one a potential channel through which terrorists can smuggle in nuclear/radiological material. Passport Systems Inc. has developed a new cargo inspection system which must be properly vetted before installation in the field. The primary objective of this project was to determine whether or not the Passport top-down radiographs were less attenuating than Non-Intrusive Inspection (NII) side-view radiographs. First, X-ray images of steel plates were analyzed to obtain a curve of attenuation vs. steel thickness. Both high- and low-resolution radiographs were analyzed and compared. The high-resolution attenuation curve flattened out at around 35 cm, while the low-resolution curve flattened out at around 40 cm. These curves were applied to radiographs of CWMD* cargo constructed to be representative of U.S. imports. As expected, the equivalent steel thickness for CWMD cargos closely tracked bulk density. A general correlation was found between equivalent steel thicknesses from side-view and top-down radiographs of CWMD cargos. For all but one cargo, cement, the top-down and side-view radiographs had similar equivalent steel thickness, thus attenuation.



*Countering Weapons of Mass Destruction (CWMD) was formerly called Domestic Nuclear Detection Office (DNDO)

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Introduction

Because millions of cargo containers enter the United States each year, there are millions of opportunities for terrorists to smuggle in dangerous radiological or special nuclear materials. The Department of Homeland Security (DHS) has been tasked to ensure that the United States remains safe from the illicit transportation, development, or procurement of a radiological/ nuclear (R/N) device or materials. The Nuclear and Radiological Imaging Platform (NRIP) program within DHS/CWMD aims to develop and characterize the performance of an integrated R/N detection platform and to determine if it performs better than previous screening systems. The cargo scanner developed by Passport features several technologies that have never been fielded, including the subsystem that my project involved. I concentrated on the high-energy X-ray transmission imaging subsystem for producing 2D (top-down view) attenuation images. This subsystem was created to help identify highly-attenuating potential threats, but I focused on a smaller, more specific topic for my project. I worked on converting attenuations in the top-down X-ray transmission images into equivalent steel thickness. For example, a slab of material with a given attenuation would be converted into an equivalent thickness of steel that would have the same attenuation. Equivalent steel thickness provides a consistent way to compare data acquired by different inspection systems.

Description of the Research Project

DHS CWMD aims to foster development of our border's defenses through a new cargo inspection system. Previous studies have shown that threat detection and false alarm rates depend on cargo density and complexity. As part of the NRIP program, a CWMD team collected radiographs from a top-down X-ray inspection system developed by Passport Systems, Inc. and side-view radiographs from an NII system developed by Smiths Detection. This project investigated whether or not the Passport top-down radiographs are less attenuating than Non-Intrusive Inspection (NII) side-view radiographs.

The objectives of this study were:

- Determine how well a 9 MeV X-ray imaging system penetrates steel;
- Characterize CWMD cargos in terms of equivalent steel thickness and compare with cargo bulk properties such as density;
- Compare results with a side-view inspection system.

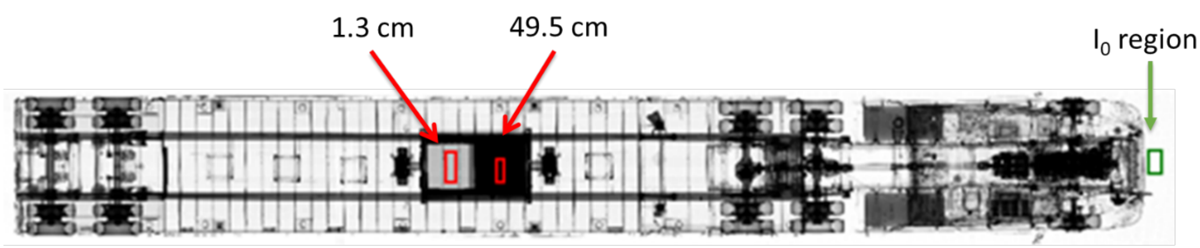

Figure 1. Top-down radiographic images of steel plates on truck trailer. Regions of interest are indicated by red boxes and plate thicknesses are as indicated.

First, I compiled X-ray transmission images of steel cargos and developed a Python script that computed the mean intensity from the selected regions of interest. The images contained plate assemblies ranging from approximately 1 cm of steel to 50 cm of steel, an example of which is shown in Figure 1. The regions of interest were determined manually for each image to avoid including extra metal from the trailer. The amount of transmitted x-ray flux, I, was expected to be approximately described by Beer's Law: $I = I_0 e^{-\mu L}$, where I_0 is the incident flux, μ is the material-dependent linear attenuation coefficient, and L is the thickness of the material (steel plates in this case). Therefore, a quantity known as radiographic attenuation, $-\ln{(I/I_0)}$, was calculated to approximately linearize the dependence on steel plate thickness. The results are shown in Figure 2 for both low- and high-resolution images, which shows that that the low-resolution curve flattens out at around 40 cm (ignoring the outlier), while the high-resolution curve flattens out at around 35 cm. The straight, black, dotted line is projected from the first few points of data. Both curves begin to deviate at around 20 cm. The low-res curve takes longer to flatten out, so there is more penetration of the steel plates than in the high-res subsystem.

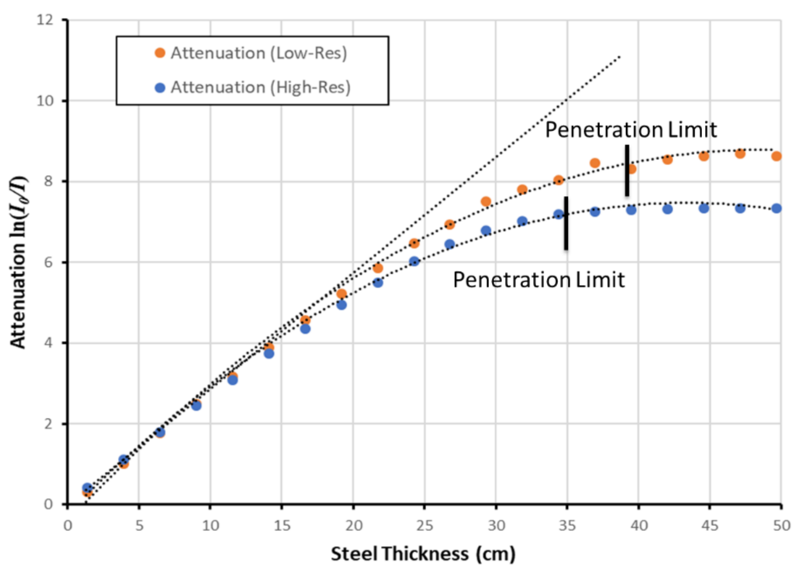

Figure 2. Measured attenuation values for steel plates of varying thicknesses.

I compiled the attenuation information into a lookup table that could be used to convert radiographic attenuation to equivalent steel thickness. I checked the validity of the lookup table by applying it to the original steel plate images and verified that it recovered the expected thickness values. Then I compiled the X-ray transmission images for CWMD cargos (designed to represent U.S. imports), converted from irradiance units to attenuation units, then analyzed the regions of interest of the cargos with the lookup table to find the equivalent steel thickness of each cargo.

I drew the regions of interest to capture as much of the actual cargo as possible while omitting the empty areas between cargo pallets. An example image with defined pallet boundaries is shown in Figure 3.

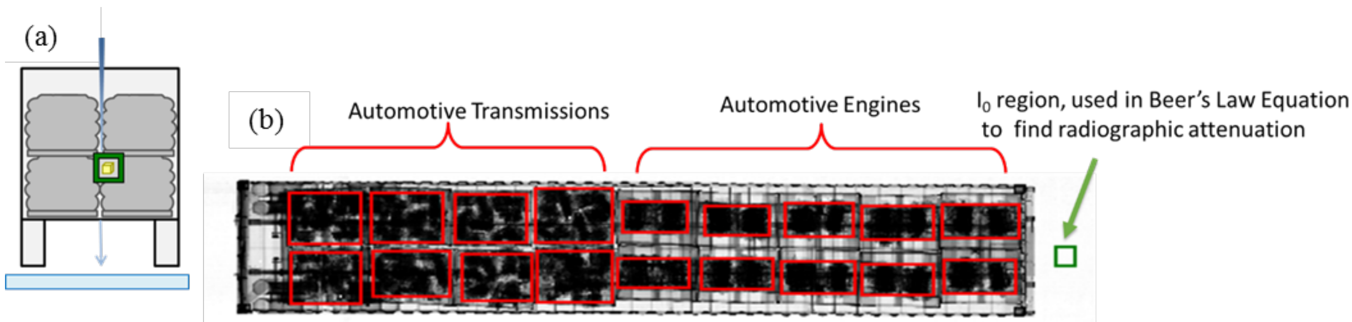

Figure 3. Diagram of top-down radiographic imaging system (a) and example top-down radiograph of a trailer filled with pallets of automotive transmission and engines (b). Cargo boundaries are shown as red boxes and the region used to measure I_0 is shown as a green box on the right side of image.

I again used Beer's Law to convert each cargo image into attenuation units, then applied an equivalent steel thickness lookup table based on Figure 2 to obtain an equivalent steel thickness image. An example is shown in Figure 4. I repeated the entire process for the low-resolution images.

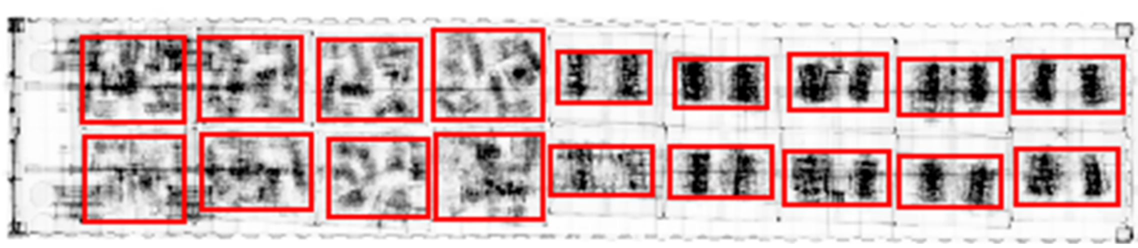

Figure 4. Example top-down radiograph of automotive engines and transmissions after converting to equivalent steel thickness. Red boxes indicate pallet boundaries. In this grayscale rendering, pure black corresponds to 30 centimeters of equivalent steel.

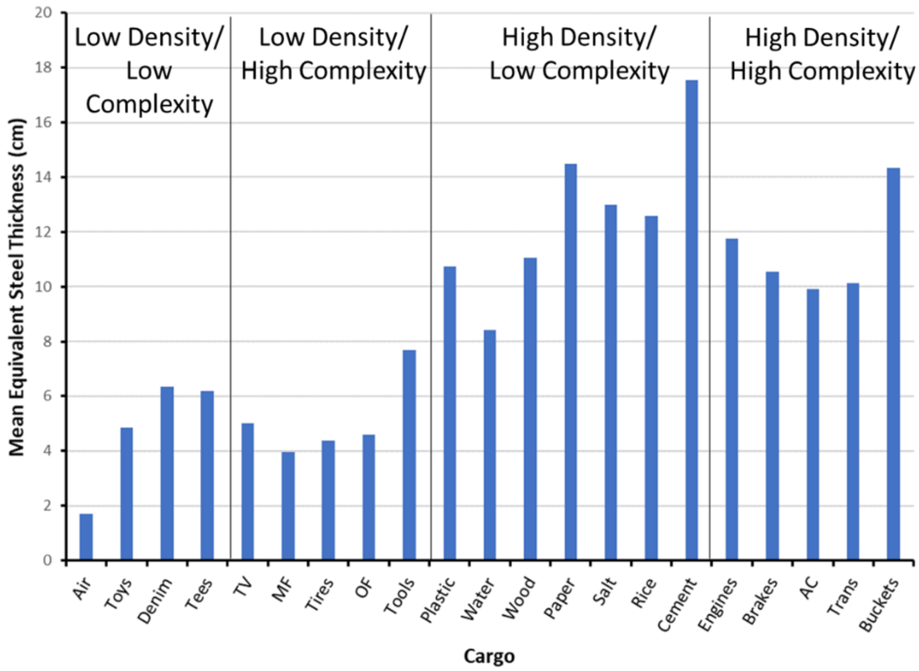

Figure 5. The mean equivalent steel thickness for each CWMD cargo from top-down radiographic images. Value are sorted from left to right by increasing cargo bulk density within each cargo density/complexity category.

Once the steel cargos had been analyzed and the attenuation curves found, it was time to analyze the various CWMD cargos. As shown in Figure 5, the equivalent steel thickness for CWMD cargos closely track cargo density categories, as expected. Cement is the densest cargo, followed by paper and buckets. Air (empty space within a container) is the least dense, and reflects contributions of the container floor, the axles, and the chassis. The reason why the measurements do not monotonically increase with density is that areal density was not considered, i.e. some cargos were stacked higher than others.

To quickly verify that the CWMD cargos were being characterized correctly, I plotted equivalent steel thickness against areal density (bulk density multiplied by thickness of cargo) as shown in Figure 6. A strong positive correlation was found, as expected.

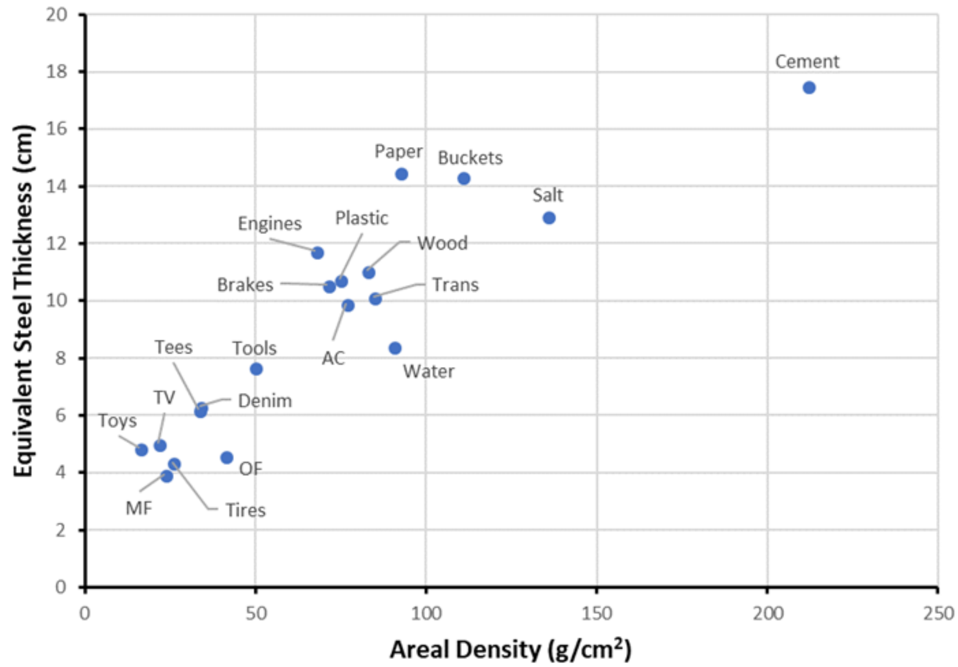

Figure 6. Equivalent steel thickness versus areal density for the 19 CWMD cargos.

Once I had obtained mean equivalent steel thicknesses of 19 CWMD cargos, I was able to compare with results from similar experiments with side-view imaging systems. An example side-view image is shown in Figure 7.

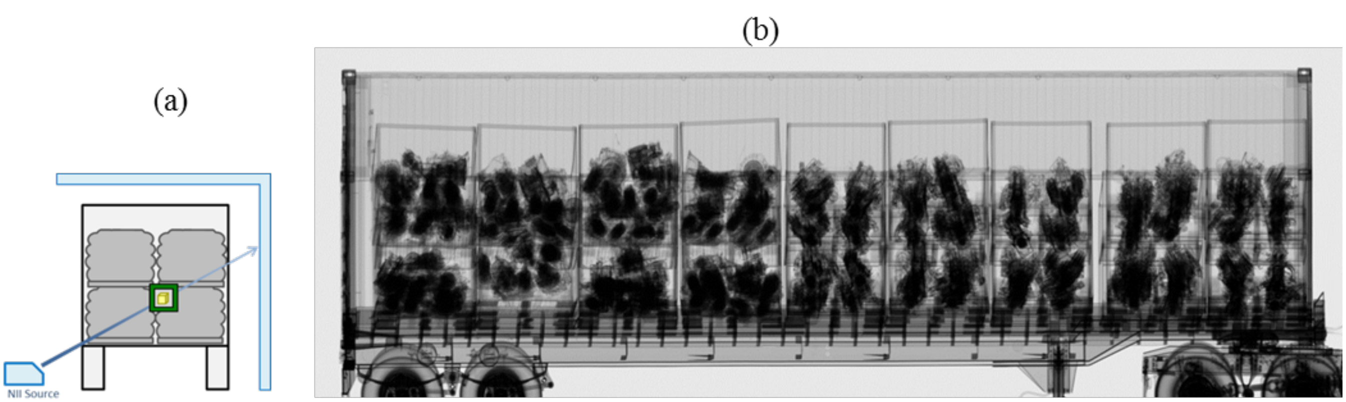

Figure 7. Diagram of side-view radiographic imaging system (a) side-view transmission radiograph of automotive transmissions and automotive engines (b).

As shown in Figure 8, I compared these results to those obtained from a previous experiment, which differed only in that the cargo was imaged from the side rather than from above [1] [2]. The top-down images might be expected to have higher attenuations due to the container floor, chassis, and axles, but cargo loading impacts the measurements. A comparison of equivalent steel thicknesses from side-view vs top-down radiographs shows that they are correlated and similar for all cargos except cement. Cement is an outlier due its height being small relative to its width. As shown in Figure 9, Cement is about half as high as it is wide wide in order to meet weight constraints. Performance difference should be expected for cement, and other dense, single-high cargos. More work is needed to determine if top-down radiographs show complexities similar to side-view radiographs.

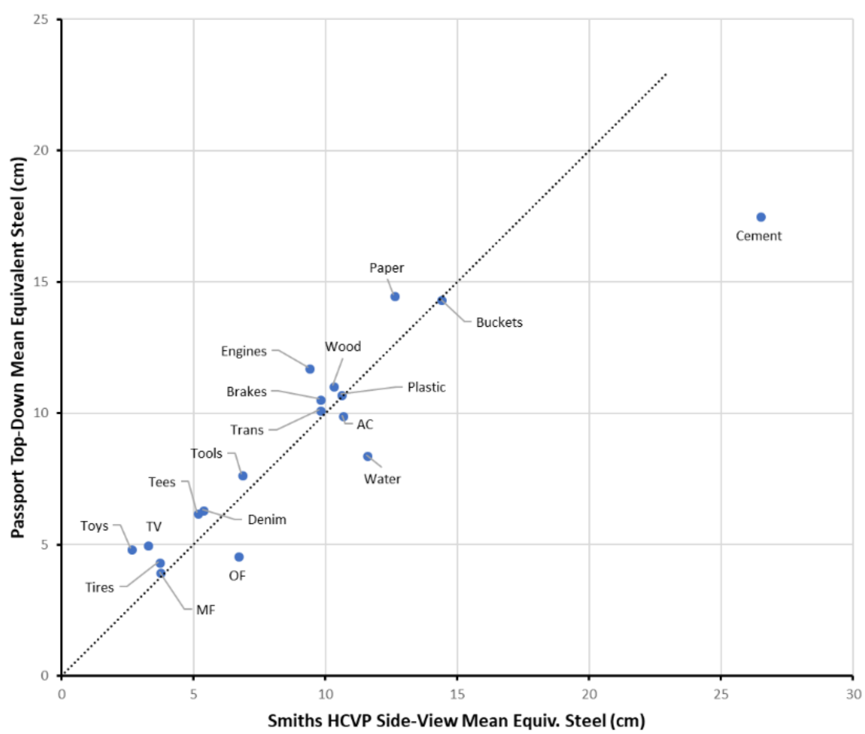

Figure 8. Comparison of CWMD cargo equivalent steel thickness measured by top-down and side-view radiographic imaging systems.

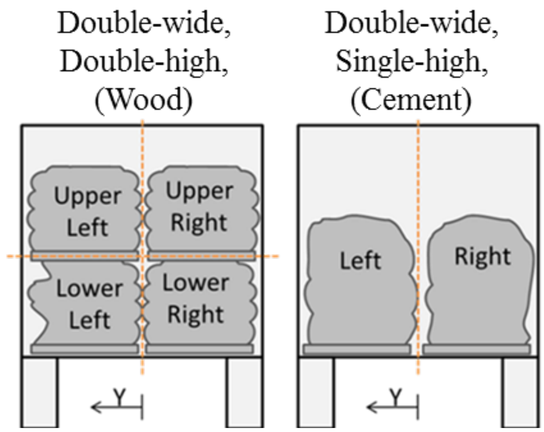

Figure 9. Cargo loading pattern examples. Both the Wood and Cement cargos had similar widths, but the Cement cargo was only about half the height of the Wood.

Contributions Made to the Research Project

This entire project was carried out by me, with aid and direction from my mentors, Steve Glenn and Chuck Divin. Therefore most contributions and accomplishments discussed in this paper are mine. Nothing was published, but I did present my work to a group of scientists who are working on the same Passport inspection system. I also presented a poster at the lab's annual student poster symposium.

What new skills and knowledge did you gain?

At the beginning of the summer, my primary programming language was C++. I knew some Python but had to learn how to use it effectively. At the beginning, I got some practice with simpler topics in Python before moving on to image analysis and data processing. I now feel comfortable with Python in general and with these other topics. I also learned some handy new functions of Microsoft Excel, PowerPoint, and Word.

Research Experience Impact on My Academic/Career Planning

Working in the Nondestructive Characterization Institute (NCI) at Lawrence-Livermore National Lab has been interesting. I think my experience here has led me to feel confident in going to grad school once I graduate; most of this decision comes from talking with all sorts of people, lab employees and other interns, who universally advocate for grad school. Another reason why grad school seems like a better option is that I want to be able to do more in my job than just write code for data analysis – I'd like to have more input with the experiments themselves and work on a wider variety of projects. I want to be smarter and have more responsibility, and I think that comes with grad school and the jobs that follow. Working in NCI has really hammered in my lukewarm feelings toward programming – when I go back to school, I want to get involved in experimental research so that I can have a more hands-on approach to my work. I've been working on a team at school mainly focused on analyzing data from a sounding rocket, but the phenomenon isn't particularly fascinating to me. As a physics major, I want to double down on the field and start to do research on more physics-related topics. I've heard that there is a good nuclear physics program here at the lab, and that is a potential area of interest for me. I also have tentative plans to join a dark matter detection project at Penn State, name LZ, which LLNL is a founding member of and employs researchers for. As far as the lab goes, it seems to be a very well-regarded place to work, and a relatively enjoyable place to work. The science done here is fascinating all across the board, and the atmosphere that I've been exposed to is very attractive. Not to mention, the location of LLNL within California is beautiful – I've been exploring all kinds of places every weekend since I've been here, and I still feel like there is plenty still left to do next time I come back. The presence of 800 other interns made making friends quite easy, and I hope to see many of them again, whether at the lab or elsewhere. I will definitely apply for another internship at this lab next semester, likely through CWMD again, as the package offered is amazing and the work done is applied in such a noble way. Although, I will likely end up applying to the lab again through a variety of programs to give myself a better chance of coming back. I'm not sure whether I would apply to NCI again or if I would apply to another area, but that's something that my research experiences next year at school should help me figure out. Either way, I hope that my mentor and/or other members of the team would want to put in a good word for me.

Relevance to the mission of DHS

The relevance is described in detail towards the beginning of the paper. Programs within DHS specifically tasked Passport to create this cargo inspection system, and now this team at the lab is checking the data obtained by the system to verify that it is functioning well. The potential dangers of radiological or special nuclear materials being smuggled into the United States are obvious, and this work is a step towards preventing these dangers.

References

[1] J. Pashby, et. al, "Radiation Detection and Dual-Energy X-Ray Imaging for Port Security," LLNL-POST-735791, 2017.

[2] N. Birrer et. al, "Characterizing Density and Complexity of Imported Cargos," LLNL-POST-735787, 2017.

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