Radiography Design Contest

The Penn State Radiation Science and Engineering Center uses the Breazeale Nuclear Reactor to take images using the neutrons emitted from the fission process of uranium atoms in the reactor fuel.

Similar to X-rays which are blocked by bone and thus can be used to observe broken bone through soft tissue, neutrons will be blocked by some materials and pass through others. We can quantify the likelihood that X-rays or neutrons will be attenuated (blocked) by absorption or scattering using a measurement called an attenuation coefficient. The attenuation coefficients for various elements are graphed in *Figure 1.*

As shown in *Figure 1*, X-rays will be attenuated more as the atomic number and thus the electron density of the material increases. The blue line shows that diagnostic X-rays (150 kV) will pass through low atomic number elements such as hydrogen, carbon, and oxygen. Calcium partially blocks the x-rays. The more calcium that is present (thicker bone or tooth), the more x-rays are attenuated. Cadmium and lead (higher atomic number) easily block diagnostic X-rays.

Element	Symbol	Atomic #
Hydrogen	H	1
Carbon	C	12
Calcium	Ca	20
Cadmium	Cd	48
Lead	Pb	82

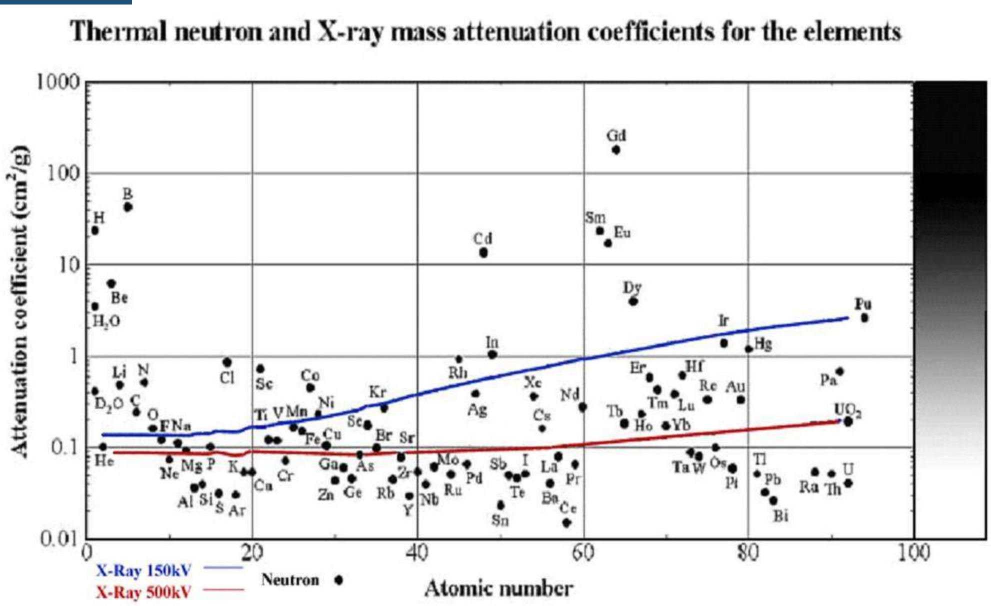

Figure 1: Attenuation Coefficients for 150 & 500kV X-rays and Neutrons for Elements by Atomic Number

Neutrons do not follow a linear relationship. The neutron attenuation as shown in *Figure 1* is depicted by the dots. Neutrons can pass through high atomic number elements such as lead, thorium, and bismuth, but are scattered away by light elements like water, carbon, and beryllium. Additionally, some elements such as boron and cadmium can absorb neutrons, stopping them in their tracks. As a result when we take neutron radiographs, what we see are the shadows caused by neutron absorption and scattering. *Figure 2* shows a neutron radiograph of a spray paint can in motion. An X-ray radiograph would show only the shadow of the can itself, resulting in a darkened rectangle on the film, because X-rays could not pass through the metal outside of the can. However, in the neutron radiograph, the neutrons pass through the metals in the can and are stopped by the hydrogen and carbon compounds in the paint. We can also see, in detail, the plastic hose that pulls the paint into the nozzle, because it too is made of these same elements.

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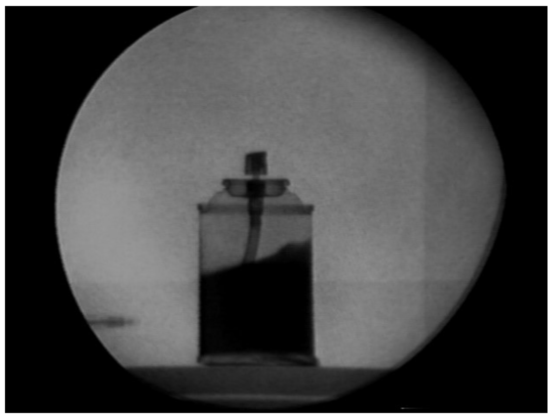

Figure 2: Neutron Radiograph of a Spray Paint Can Captured in Motion

One of many practical applications of neutron imaging is testing of neutron-absorbing alloys to find small defects. Manufacturers and regulators will want to know whether the materials hold up to environmental stresses from temperature and physical damage. We can put those materials through artificial stresses and take a neutron radiograph to find very small areas where neutrons could potentially pass through.

Another example of research done at Penn State RSEC is neutron imaging of the hydrogen fuel cell. The hydrogen fuel cell is a metal box with gas flow inlets to combine hydrogen and oxygen into water molecules. This process produces electrons which can be used to provide the energy for vehicles.

The hydrogen fuel cell cannot operate if it is opened. Nor can we see what is going on inside of it with an X-ray, because the metal walls would prevent us from seeing inside and the water molecules are too light to stop them. However, by taking a neutron radiograph, we can make measurements of the water forming and flowing through the channels during operation.

The following papers provide more information about hydrogen fuel cell research at PSU RSEC.

- Residual Water Distribution and Removal from Polymer Electrolyte Fuel Cells. M. M. Mench, J. Brenizer, K. Ünlü, K. Heller, A. Turhan, J. J. Kowai. https://www.rsec.psu.edu/assets/PDF/18-RSEC%20Book_Fuel%20Cell%202.pdf

- Neutron Radiography Measurements for Water Transport in an Operating Polymer Electrolyte Fuel Cell. M. M. Mench, J. Brenizer, K. Ünlü, N. Pekula, K. Heller, S. Çetiner. https://www.engr.psu.edu/nbg/NRMWT_FUELCELL.htm

At Penn State we developed an example to illustrate the differences between what is shown in an X-ray and a neutron radiograph. The four images below will help explain this concept.

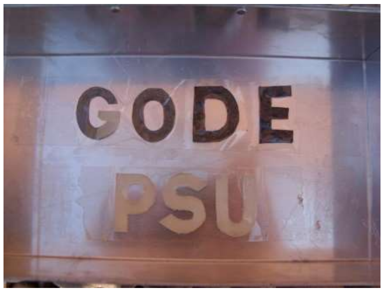

Figure 5: Photograph of Code Box

Figure 6: Photograph of Code Box with Lead Shield

Figure 5 and *Figure 6* are photographs of metal and plastic pieces arranged in a box. We originally built this inside of a cardboard shoe box, but then moved it to an aluminum box for safe keeping. Both the neutron and x-ray radiographs were taken with the lead rectangle in place as shown in *Figure 6.*

The three materials used in the design are lead, cadmium, and plastic. The “C” and “O” are made from cadmium. Because cadmium is a dense metal, it will show up in an X-ray. The “D” and “E” as well as the rectangle covering “PSU” are made from lead. Similarly, because lead has a very high atomic number, it will stop X-rays from going through. The hook turning our “C” into a “G” and the “PSU” under the lead rectangle are made from plastic. This plastic is too light to stop X-rays.

The result we get from the X-ray is shown in *Figure 7.* The image is a negative, so the places that show up dark are where X-rays have gotten through and the objects that appear in white are where X-rays were blocked.

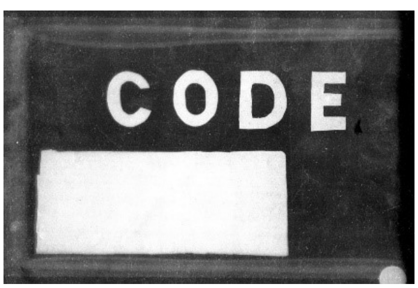

Figure 7: X-Ray Radiograph of the Code Box

Figure 8: Neutron Radiograph of the Code Box

We then took a neutron radiograph of the same box. In this case, the image is the reverse of the x-ray image, meaning the more the material attenuates the radiation, the darker the image. This time, the lead becomes more transparent because neutrons do not interact much with lead. Cadmium is a great neutron absorber, so our “C” and “O” remain. Finally, the plastic scatters neutrons, thus blocking them from exposing the film. The resulting image is shown in *Figure 8.*

Our lead rectangle as well as the “D” and “E” letters are very faint, while our plastic pieces become much more opaque turning what in the X-ray was, “C-O-D-E” into “GO PSU.”

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1955-2020
BREAZEALE
Nuclear Reactor

Design Your Own Radiograph!

The challenge we're making is for you to design your own "Code Box" which will generate two different images depending on whether we take an X-ray or a neutron radiograph.

- Create a design that will look different with (diagnostic 150 kV) X-ray and neutron radiography.
- Entries can be submitted by an individual or team
- Use the tangram shapes provided on the next page for lead and cadmium pieces. Use red for lead and blue for cadmium. Plastic pieces can be of any shape and color, so be creative!
- Remember which materials "block" which types of radiation:

Material	X-rays	Neutrons
Cadmium	Yes	Yes
Lead	Yes	No
Plastic	No	Yes

- You may overlap shapes and use as many as you like.
- Limit designs to within the 8-inch diameter circle on the last page.
- Include a title, along with a brief description of the design and how we should expect it to look in an X-ray and in a neutron radiograph.
- The entry will need to include: teacher's name, teacher's email, school, and grade.
- Please have your teacher submit your entry to rsec@psu.edu.
- Entries need to be submitted by June 1, 2020.
- The top three entries from 6-8 grade submissions and the top three entries from 9-12 grade submissions will be chosen as the winners.
- We will build the winner's designs and send the X-ray and neutron radiograph to you and your school! The final designs will also be posted to the Penn State RSEC website.