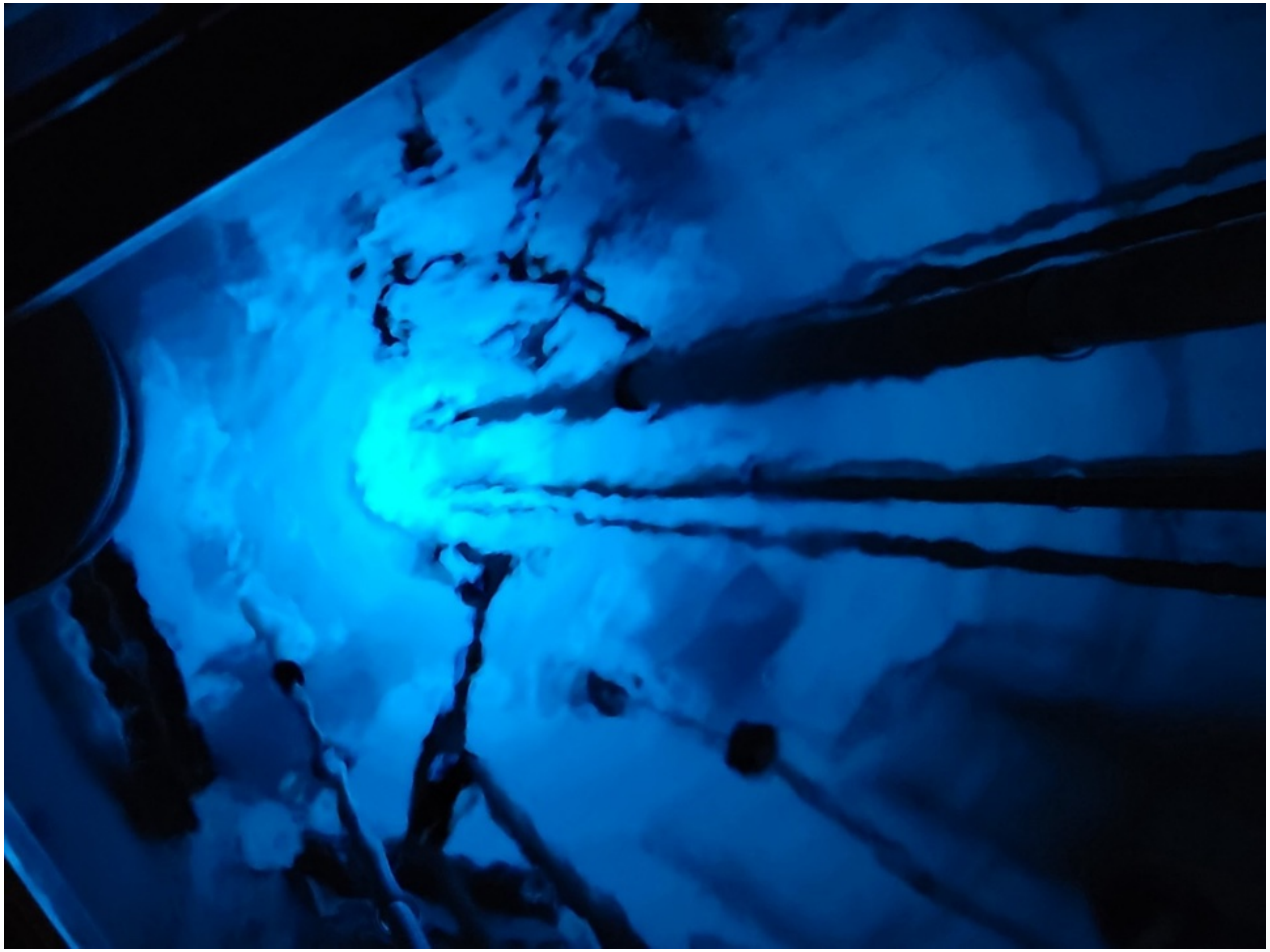
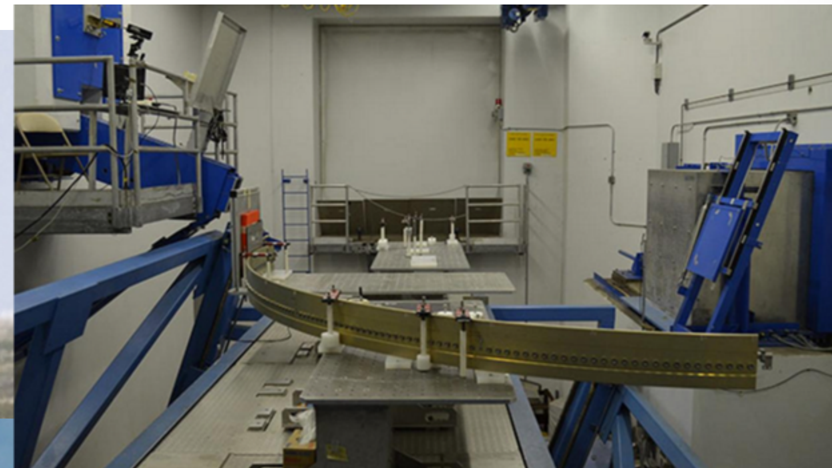
Transition from Film Based Neutron Radiography to Digital Image Acquisition for the Commercial Imaging of Pyrotechnic Devices



MNRC (1988)

Neutron Radiography on Pyrotechnic Devices.



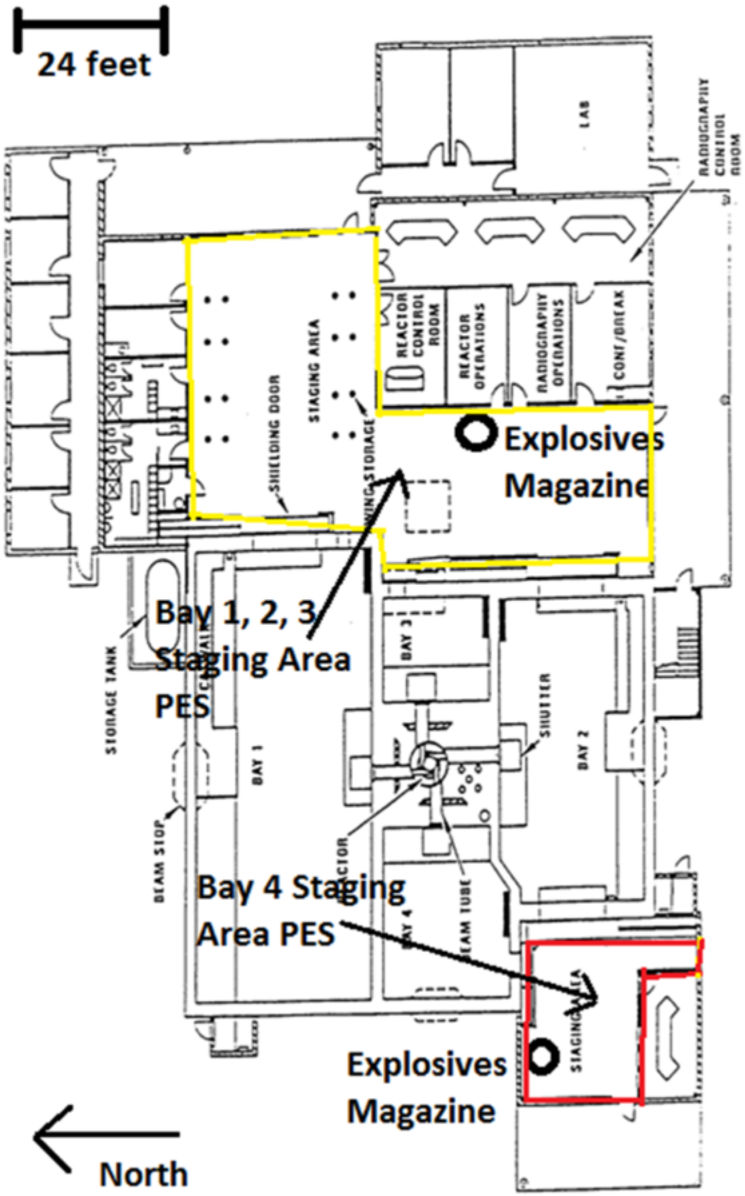
So Why Isn't Everyone Doing Commercial Neutron Radiography?

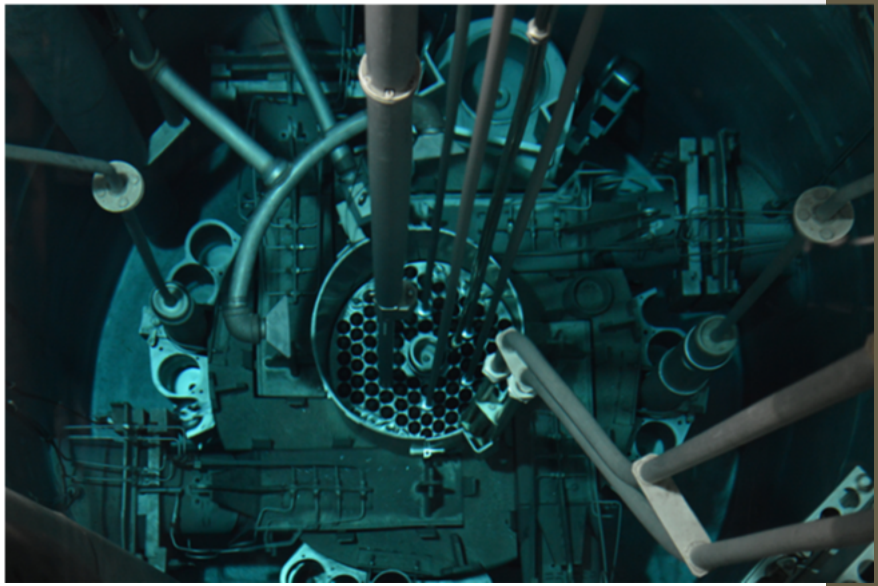
- Commercial neutron radiography in the US is still film based, while research neutron radiography is overwhelmingly digital.
- Tangential beamlines, an L/D of at least 100, large radiography bays, and a field-of-view of at least 14 by 17 inches are needed.
- Film-based neutron radiography requires a device known as a gadolinium conversion screen to sensitize the single sided x-ray film to neutrons.
- No one has successfully made high quality gadolinium conversion screens since 1990.

What Has UC Davis MNRC Been Doing The Last 8 Years?

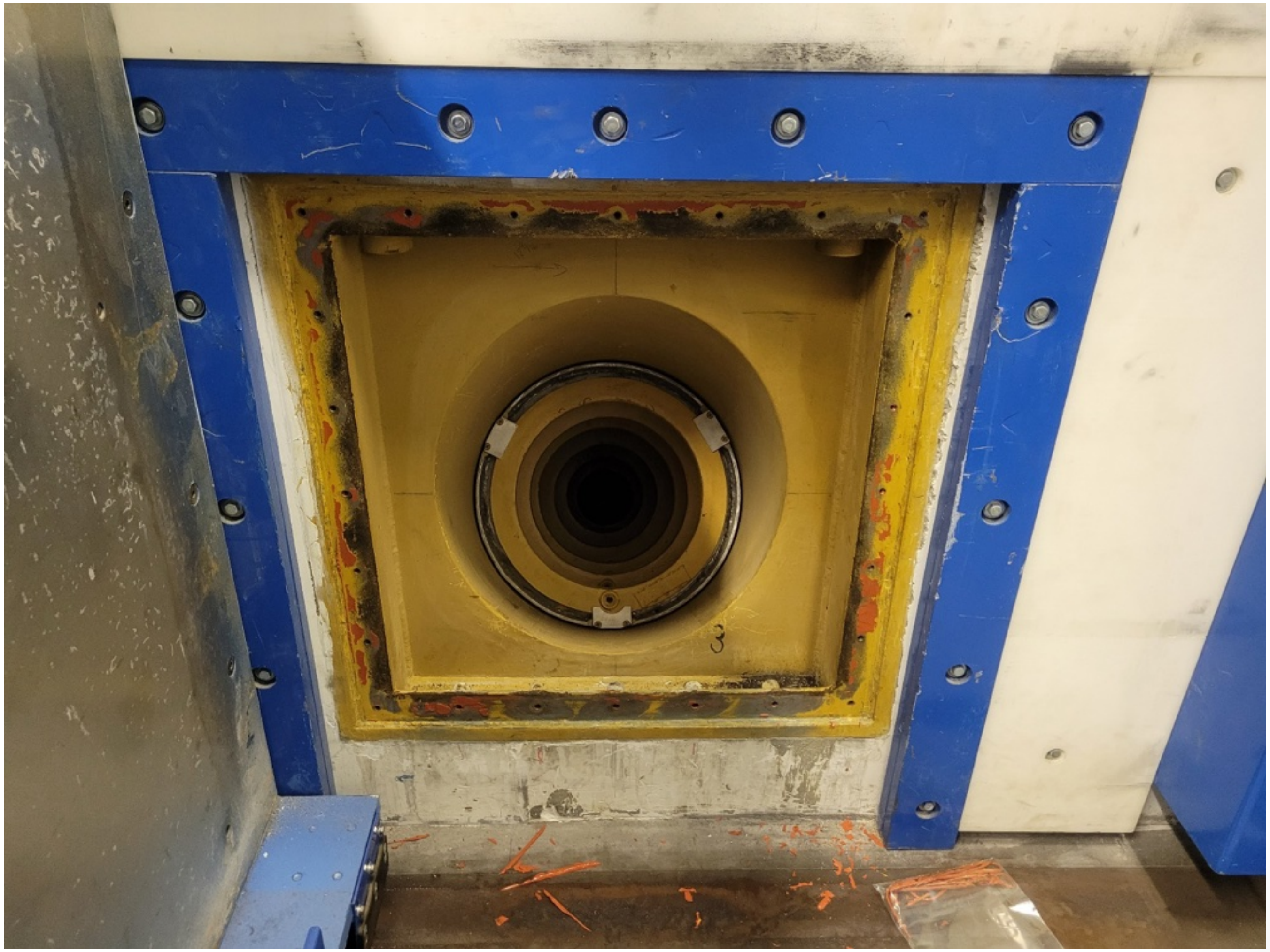
- In 2016 MNRC performed 1,500 radiographs while utilizing the reactor ~1,500 MWhrs.
- All staff from 2016 will be retired by 2025 (except for me) and industry has requested a capacity of 16,000 images per year due to GE's closure in 2023.
- Due to our dwindling fuel supply MNRC is limited to 1,000 MWHrs of reactor utilization per year.
- All while repaying 2 years' worth of operational debt, COVID, and a broken reactor in 2023.
- The good news is that total neutron efficiency for the radiography process is about 0.00000001%.
- Target efficiency is 0.00000016%.

The MNRC Facility





Bay 3 and 4



New Positioning Robots

The Gadolinium Conversion Screen

- Single sided x-ray film is only slightly sensitive to thermal neutron interactions.
- Gadolinium 157 has the largest thermal neutron capture cross section of any stable isotope of 255,000 barns with a natural abundance of 15.7%.
- 95% thermal neutron attenuation is achieved by only 25 um of gadolinium.
- Gadolinium emits a number of conversion electrons after absorbing a thermal neutron.
- The conversion electrons have ranges up to 50-100 um in water and less in gadolinium, sapphire, and film.
- These ranges match very well to the grain size/resolution of film.

Gadolinium Screen Interactions

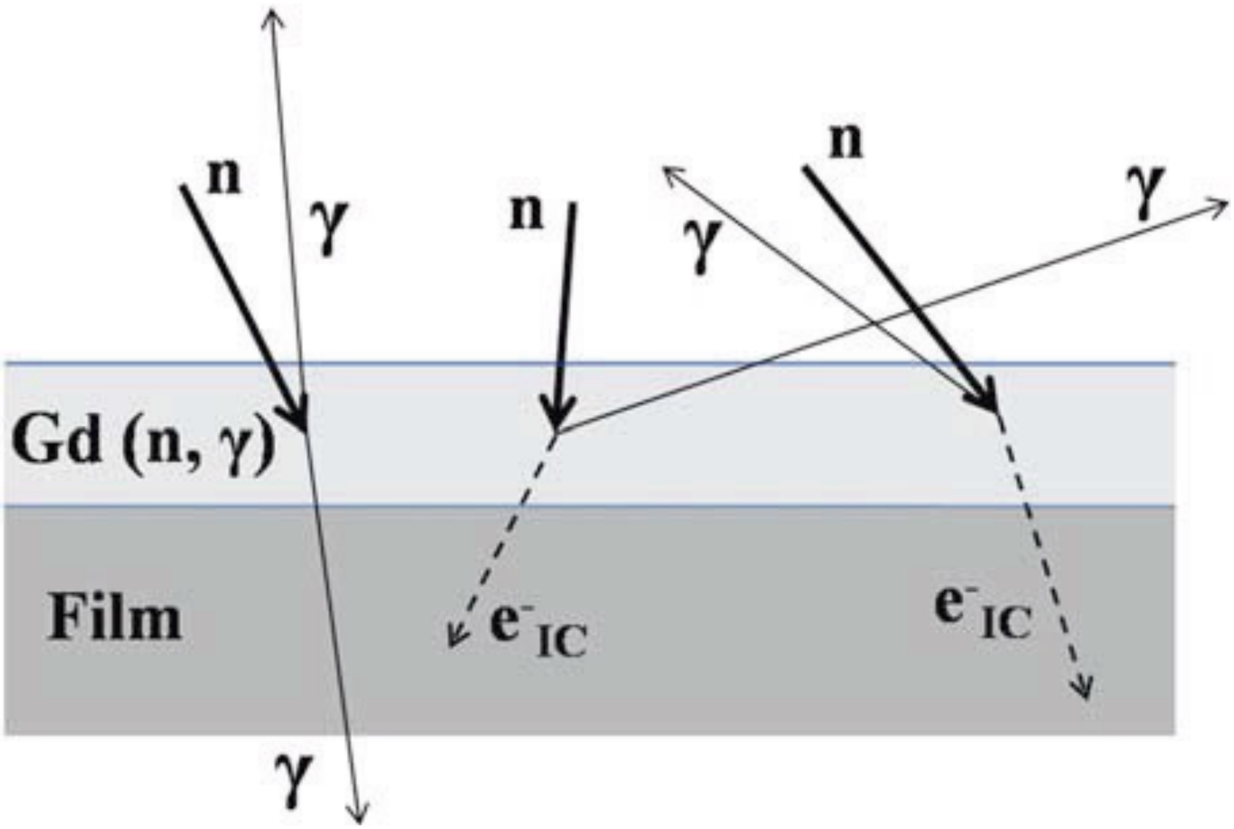


Image taken from Neutron Imaging and Applications edited by Anderson, McGreevy, and Bilheux

The Gadolinium Conversion Screen

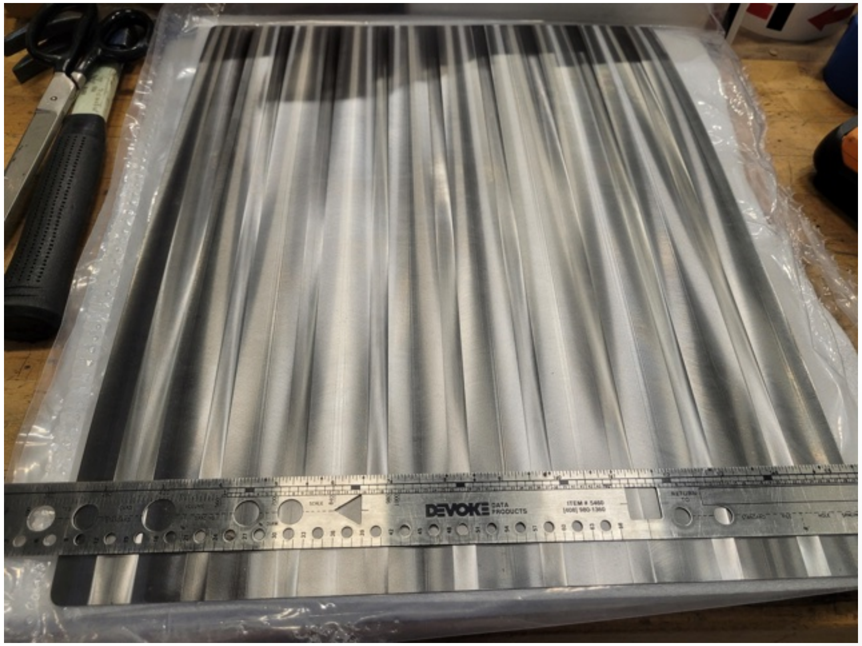
- Current screens are made on a 1/16th of an inch 6061 aluminum substrate (14 inches by 17 inches) with a 25 um gadolinium (metal) vapor deposited layer sealed by a 25 um sapphire protective layer.
- Our current screens have held up well, but any flaws introduced into the screens cannot be fixed.
- With 14 screens at MNRC they have become a bottleneck.
- The lack of new screens are also a limitation to other facilities doing or interested in doing commercial neutron radiography.
- The optical coating industry was not excited about the potential project.

Rethinking The Gadolinium Conversion Screen

- The screen must be gadolinium based and 14 by 17 inches.
- The critical dimension is not 25 um of gadolinium. A conversion screen needs only to be <u>at least</u> 25 um thick. Neutrons penetrating past 25 um essentially leave the system.
- The actual critical dimension is the protective layer.
  - Too thick will completely attenuate the conversion electrons.
  - A non-uniform thickness will non-uniformly attenuate the conversion electron resulting in a non-uniform exposure.
  - Too thin of a layer may not sufficiently protect the gadolinium.
  - No protective layer may not protect workers or the facility.
- After thinking about it for 2 years, why not just try a slab of gadolinium metal?

Making New Screens

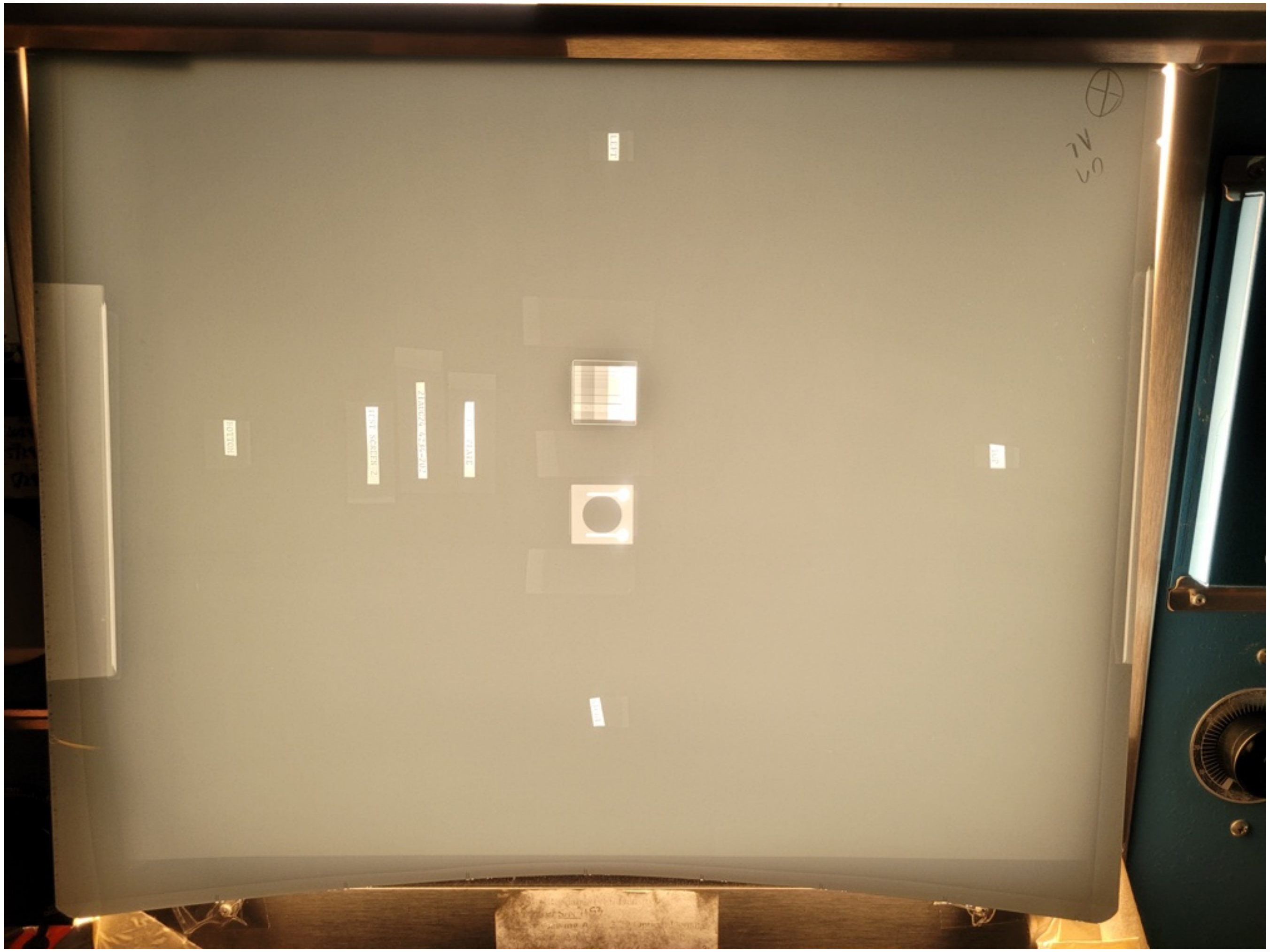
Making New Screens



Making New Screens

- The metal plates were made to size. 14 inches by 17 inches by 1.0 mm.
- Graphite gadolinium inclusions had to machined off using a fly cutter under flood coolant to machine off 20-30% of the plate’s thickness.
- Final sanding was performed to remove machining marks and any remaining inclusions.
- Finished plates were epoxied to a 1 mm thick aluminum backing to add rigidity.
- Finally, the protective layer was added.
- The end result was 14 new screens costing 1/3rd of the cost of used screens, repairable if damaged, 20% less image acquisition time, and still ASTM category 1.
- MNRC is on track for a capacity of 20,000 images per year by mid 2025.

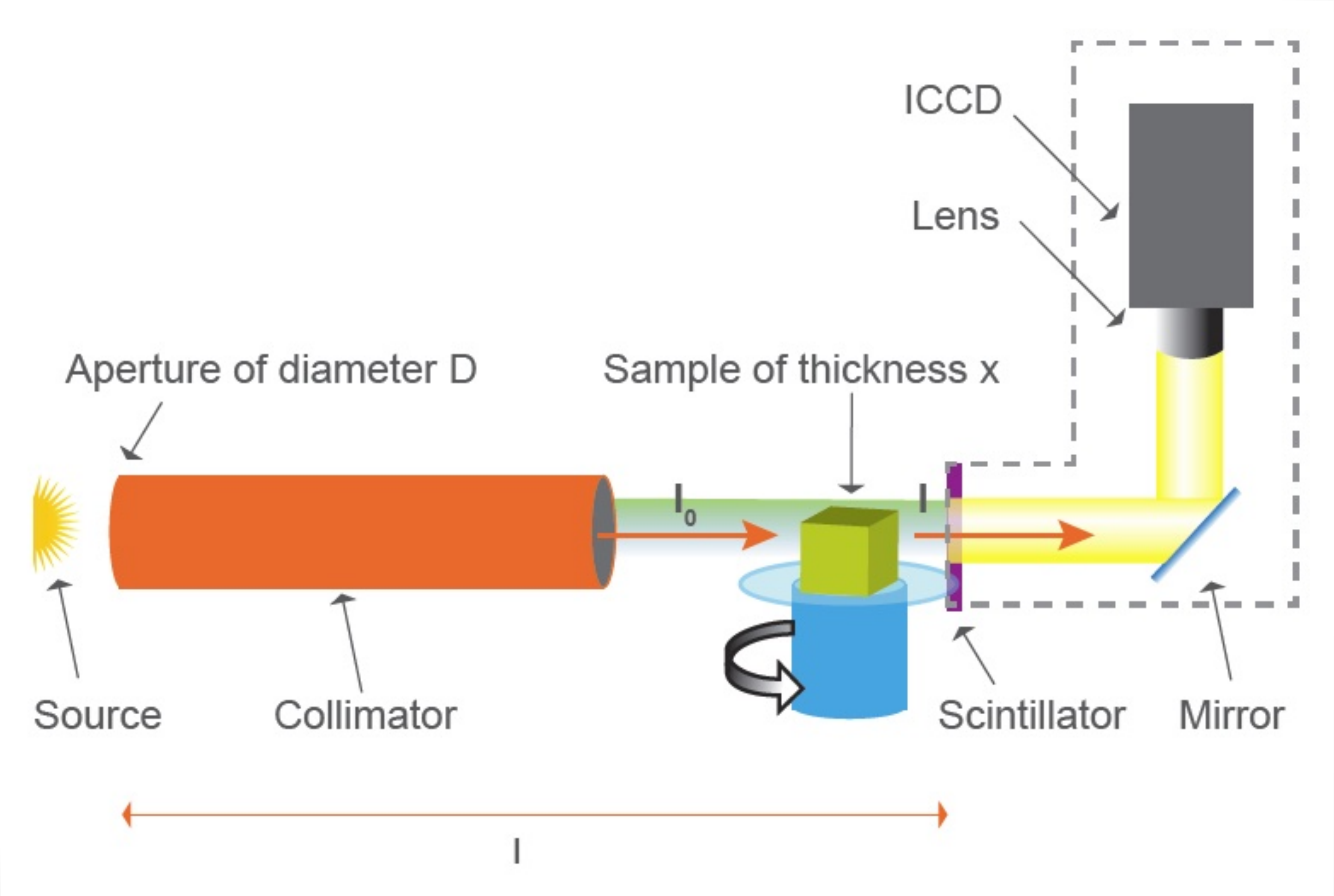
The Results



Why Are We Still Using Film in 2024?

- It has a large field-of-view.
- Sufficient gamma-ray discrimination.
- Insensitive to background radiation.
- Good resolution and contrast.
- Basically, it is good enough!
- ASTM digital neutron standard was passed in 2023 and the indication standard is still in subcommittee.
- Digital neutron image acquisition can be used for research and internal processes unrelated to flight safety.

Digital Image Acquisition



Digital Neutron Radiography

- Within the last 5 years digital neutron camera subcomponents become available to construct a digital neutron camera that can match the FOV and resolution of film-based systems (and not cost millions of dollars).
- Scintillation screens can be gadolinium, boron, or lithium based.
- Imaging sensor needs to be about 100 MP.
- Image acquisition time is around 1/10th that of film.
- Acquisition time and total facility image output is not a linear relationship, but digital systems could increase MNRC's output to 30,000 images per year. Or we can reduce reactor power by a factor of 10 to maintain the same imaging capacity.
- Digital image acquisition also allows for real-time 2D imaging and tomography.

Digital Neutron Radiography (So, what's the bad news)

- CMOS and CCD sensor are very sensitive to radiation damage and need to be heavily shielded.
- Annual sensor change out might of reasonable but daily change out is not an option.
- The threshold for the number of dead pixels in an image for a researcher is much higher than for the DoD.
- Even minor image processing might not be allowed.
- No distortion from the camera lens is allowed.
- Image quality indication standard is not finalized.
- How do you position samples within a few mm of the face of the camera one hundred times per day?
- ITAR and CUI concerns.

Digital Neutron Radiography

- All of the current issues associated with the implementation of digital neutron radiography have solutions (but figuring things out will take time).
- DoD and NASA will only transition to digital when they are forced to, but the option needs to be completely ready when the single sided x-ray film is discontinued, otherwise this capability in the US will be lost.
- Duplicating film was discontinued without notice in 2021 and one year later the world's supply was depleted.
- MNRC is looking for partners to develop these cameras and to potentially act as a secondary source for neutron radiography on pyrotechnics.
- The need and importance of this technique is increasing rapidly, we just need make DoD and NASA understand this.

Questions?