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Workshop on Radiographic Imaging and Applications Research and Development Recommendations for Field Radiography

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OAK RIDGE National Laboratory

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Physics Division

WORKSHOP ON RADIOGRAPHIC IMAGING AND APPLICATIONS RESEARCH AND DEVELOPMENT RECOMMENDATIONS FOR FIELD RADIOGRAPHY

May 21, 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
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LIST OF ABBREVIATIONS

a-Se amorphous selenium
a-Si amorphous silicon
AM additive manufacturing
ANSI American National Standards Institute
API associated particle imaging
ASIC application-specific integrated circuit
ASTM ASTM International (formerly the American Society for Testing and Materials)
BNL Brookhaven National Laboratory
CCD charge-coupled device
CMOS complementary metal-oxide semiconductor
CR computed radiography
CS contrast sensitivity
CT computed tomography
CZT CdZnTe
DARPA Defense Advanced Research Projects Agency
DD deuterium–deuterium
DDR direct digital radiography
DOE US Department of Energy
DQE detective quantum efficiency
DR dynamic range
DT deuterium–tritium
ESF edge spread function
FPGA field-programmable gate array
FWHM full width at half maximum
GRIT Gamma Ray Inspection Technology
ISO International Organization for Standardization
LSF line spread function
ML machine learning
MTF modulation transfer function
NEMA National Electrical Manufacturers Association
NNSA National Nuclear Security Administration
ORNL Oak Ridge National Laboratory
PDC photon-to-digital converter
PMT photomultiplier tube
PSD pulse-shape discrimination
RF radio frequency
RGD radiation-generating device
SiPM silicon photomultiplier
SNR signal-to-noise ratio
SPAD single-photon avalanche diode
SWAP size, weight, and power
TFT thin-film transistor
TOA time of arrival
TOT time over threshold
TPC time projection chamber
WORIA Workshop on Radiographic Imaging and Applications

1. EXECUTIVE SUMMARY

Nerine Cherepy, Lawrence Livermore National Laboratory
Tom Crane, Atomic Weapons Establishment
Paul Hausladen, Oak Ridge National Laboratory
Andrew Nicholson, Oak Ridge National Laboratory

WORKSHOP ON RADIOGRAPHIC IMAGING AND APPLICATIONS

The Workshop on Radiographic Imaging and Applications (WORIA) brought together subject matter experts from industry, academia, US and UK government agencies, and the national laboratories to provide a forum to liaise and share information between technology developers in government and industry, end users, and mission stakeholder to produce an "expert consensus view" regarding future research directions toward a comprehensive radiography/penetrating imaging portfolio in the Defense Nuclear Nonproliferation Research and Development Near Field Detection Portfolio. The inaugural WORIA was held at the Spallation Neutron Source at Oak Ridge National Laboratory on Feburary 7–9, 2023. The inaugural WORIA meeting focused on field radiography applications, or situations in which a portable imaging system must be brought to an item of interest (rather than the item brought to an imaging facility). This report documents consensus views derived from the meeting and provides research and development recommendations for federal program managers.

The inaugural WORIA meeting was divided into the following eight discussion sessions:

Session 1: Government and Industrial Applications of Radiographic Imaging

Session 2: Field Use Applications

Session 3: Radiographic Imaging System Integration

Session 4: Radiography Standards

Session 5: Detector Materials

Session 6: Readout Electronics

Session 7: Radiation Source Development

Session 8: Algorithm Development and Data Fusion

Session 1 provided a forum for federal program managers or their designees from the US Department of Energy/National Nuclear Security Administration, Department of Homeland Security, and the United Kingdom to give an overview of the program and their interests in radiography. The other seven sessions were technical and were led by at least two session co-chairs, who presented the current state of the art for each topic area and proposed future R&D topic areas. Presentations were followed by time for discussion/question and answer with WORIA attendees. The primary purpose of these sessions was to generate genuine discussion and exchange regarding future areas of R&D for each topic area. Each session had assigned personnel who took notes on the discussion for posterity, and a survey with questions for attendees was distributed and collected for each session.

In addition, WORIA held a long-form poster session each day where WORIA attendees presented their current research, focused around the technical sessions presented that day. The poster sessions provided a forum for participants to showcase technologies relevant to the workshop. This format enabled in-depth conversations between participants that are not typically possible in a presentation format.

To help motivate and direct discussion, each discussion session sought to address cross-cutting challenges in field radiography identified by the organizing committee. The following cross-cutting challenges were identified for the inaugural WORIA:

Material Identification: Potential approaches can exploit differences in attenuation between multiple particles (e.g., x-rays, neutrons), multiple energies of single particles, or differences in the amount and angular distribution of scattering. Sensitivity to these differences can be achieved by using multiple sources or detectors with energy discrimination, control of source energy spectrum, or by using absorber gratings. Fast algorithms are required to interpret data in near real time.

Improved signal-to-noise ratio (SNR) in count-limited and/or scatter dominated domains: Potential approaches include methods to reduce sensitivity to scattered flux via directional source emission, physical collimation, or coincidence collimation; fast gating of detectors to reduce integration of noise when the source is not on; and detectors that are more efficient to the signal of interest (e.g., MeV x-rays) by increasing detector efficiency or by implementing energy-binned detectors that can separately image the higher energy interactions of interest.

3D imaging: Potential approaches include time-of-flight imaging and few-view tomography with sparsity in some quantity (e.g., entropy, gradient magnitude).

Single-sided imaging: Approaches that enable single-sided imaging in addition to traditional transmission imaging are highly desirable. Potential approaches include x-ray backscatter imaging and neutron inelastic scatter imaging.

Improved resolution with MeV interrogation: Potential approaches include MeV microbeam sources and pulse-counting detectors that can centroid multiple pixels involved in a track.

Gains in practicality: Gains in practicality include substantial improvements in ruggedness, reliability, portability (reduced size, weight, and power), or timeliness of measurement or analysis. Gains in practicality also include substantial reductions in cost, complexity, or other barriers to deployment.

1.1 HIGHEST PRIORITY R&D RECOMMENDATIONS.

This report combines the findings from the session chairs and suggestions by WORIA attendees. The following sections summarize the current state of the art and R&D recommendations. The highest priority R&D recommendations, from all topic areas, were chosen by the WORIA executive committee and session chairs and are listed in the following subsections.

1.1.1 R&D Recommendation 1: Detectors for Penetrating Field Radiography

Penetrating field radiography requires flexible, position-sensitive, large-active-area (1,000–2,000 cm^2) detection systems to minimize measurement time when multiple exposures are required. These detection systems should be low power (~25 mW/cm^2) to achieve long working times using batteries that are readily transportable, have high efficiency (≥10% efficiency for 14 MeV neutrons or ≥5% for 1 MeV x-rays) and high spatial resolution (≤0.5 mm for MeV x-rays and 2–3 mm for fast neutrons), and have good background rejection. Successful approaches will combine R&D in construction of position-sensitive scintillator arrays or solid-state materials and readout electronics.

These goals can be achieved using either pulse-integrating or pulse-counting detector systems, although exact requirements to meet the goals described above using either technique will vary. For pulse-counting neutron detectors, fast timing (<0.5 ns full width at half maximum), energy binning, and neutron–gamma discrimination are desirable to reduce backgrounds. For integrating detectors, reduction in dark current via detector gating while the source is on is desirable, provided the implementation improves the SNR. Enabling technologies such as fast timing and higher spatial/energy resolution will permit single-sided and/or multi-energy radiography.

1.1.2 R&D Recommendation 2: Common Radiography Standards and Test Objects

Common standards and test objects are needed for x-ray and neutron radiography system development and evaluation. Standards and test objects provide a common reference for developers and users to understand the performance of different radiography systems, and they provide a way to monitor performance of these systems over their operational lifetimes. The span of standards and test objects includes (1) a set of procedures to evaluate radiography systems, (2) a physical object that can be reproduced at multiple laboratories, (3) benchmark datasets for algorithm development, or (4) validated simulation tools that can be used to create rich synthetic datasets. Although many locally developed standards and test objects exist, community consensus is lacking on which are useful for a variety of applications to understand system performance metrics such as resolving features and/or material discrimination. Common standards and test objects are particularly needed for fast neutron radiography systems because no formal standards exist for these systems. Instead, standards and test objects have been assembled by different research groups to meet their needs.

1.1.3 R&D Recommendation 3: Tunable X-Ray Sources with Improved Size, Weight, and Power

Although R&D is presently being pursued in this area, WORIA would like to emphasize the importance of continuing investment. New x-ray sources with significantly smaller size, weight, and power than present commercial products but with tunable x-ray endpoint energies ranging from 1 to 9 MeV and small spot sizes are needed to increase penetration in heavily shielded materials, reduce measurement times, and identify materials. Continued longer term R&D is needed to develop potentially high-impact capabilities such as adjustable energy spectrum, ultrafast pulses, and very small spot size. The ability to provide logic signals to synchronize pulsed sources with detector systems for increased SNR is preferred. The ability to accurately monitor source output on target is also desirable. The development of these systems should be closely coordinated with end users to ensure the trade space is sufficiently tailored.

1.1.4 R&D Recommendation 4: Fast Neutron Sources with Improved Size, Weight, and Power

Although R&D is presently being pursued in this area, WORIA would like to emphasize the importance of continuing investment. New robust, compact, tunable, high-yield (5×10^8 n/s for API or 10^{10} n/s for non-API) MeV neutron sources are needed to increase fieldability and reduce measurement times. For non-API sources, high intensity is needed to enable image acquisition substantially faster than the accumulation of dark current. For API sources, improved alpha detectors (in rate capability, timing, and spatial resolution) are needed to take advantage of the full capabilities of improved sources. These systems should have $\leq$2 mm spot size and be able to operate for >1,000 h. The development of these systems should be closely coordinated with end users to ensure the trade space is sufficiently tailored.

1.1.5 R&D Recommendation 5: New Detector Materials for X-ray and Neutron Radiography Systems

Key properties of detector materials determine performance for field radiography systems using MeV x-rays and fast neutrons include the stopping power (density and interaction cross section); the efficiency of conversion of ionizing radiation to light (scintillators) or electrons (solid-state detectors); characteristic conversion times such as decay time and afterglow; resistance to mechanical shock, thermal shock, and chemical insult; and long-term stability. Furthermore, materials should be amenable to a scalable process to build large-area position-sensitive detectors at reasonable cost that have sufficient detection efficiency, spatial, energy, and timing resolution, minimize ghost images, and are suitably rugged. Often, these desirable properties are in conflict, and a balance between different material properties must be achieved. For instance, optimizing a material on ruggedness alone can have a detrimental effect on light output. From the detector system side, increasing efficiency by increasing detector thickness typically reduces resolution and/or collected scintillation light.

New R&D is needed to discover and optimize detector materials and to process these materials into configurations useful for penetrating imaging applications.

1.1.6 R&D Recommendation 6: Radiography Algorithm Development and Data Fusion

Algorithms, data fusion, and visualization collectively are used to collect data and process, display, or interpret them in a way that supports decision-making. Algorithms for field radiography include functionality to support feature detection and identification by the operator as well as to measure the feature's dimensions.

Collecting sufficient information within the constraints of a field measurement is challenging because time and equipment are fundamentally limited. Including knowledge of the setup geometry and constraints that might be present on the object of interest into a physics-informed model or a data-informed model can be a powerful tool for improving understanding of the scene and object of interest. Disparate measurements, physical models, and problem-set knowledge may be leveraged to improve image quality, reduce data collection requirements, and provide a more detailed understanding of object properties in penetrating imaging applications. Prior understanding can be represented via physical modeling or via empirical representations such as machine learning. Lightweight algorithms that can quickly provide results using computational resources available on a laptop are clearly of value. However, a role may also exist for more computationally intensive or slower methods, in which information is passed to an off-site computational facility or to off-site experts for processing, provided the amount of information that needs to be passed is small.

Research topics for algorithms in penetrating imaging include the following:

- Combining physical measurements for enhanced understanding, including combinations of low- and/or high-energy x-ray and neutron radiography systems to improve material identification, multiple views for 3D representations of an object, or combining active and passive data for improved object descriptions.
- Leveraging physical knowledge or external information for enhanced understanding, including the use of fast (physical) forward models to iterate toward an object model consistent with data, using assumptions or prior knowledge to constrain possible results, and identification of known items within an object.
- Automating estimates of instrument position via scene-generation tools, easing the burden on operators while supporting more complex modeling and algorithms such as computed tomography.

An understanding of uncertainties is critical for sound decision-making. Maintaining an understanding of uncertainties in the face of sophisticated data processing algorithms can present a challenge and should be considered as part of algorithm-development efforts. Finally, algorithm outputs that combine multiple data streams or information sources can be complex and may benefit from improved visualization tools. Improved visualization methods could support displaying uncertainties in radiography data streams, complex data/algorithm output, and 3D scene renderings with overlaid or combined imagery such as x-ray, neutron, and/or optical.

2. CURRENT STATE OF THE ART IN FIELD RADIOGRAPHY

Burke Kernen, Sandia National Laboratory

2.1 RADIOGRAPHY IS A CRITICAL FIELD DIAGNOSTIC

Radiography is one of the primary diagnostics in any field application for nondestructive testing. It is the very first active diagnostic employed and usually is preceded only by passive safety scanning to determine the extent of hazards that may exist to personnel.

Before any attempt at dismantling or containing any hazardous device, a full understanding of the structure, internal and external geometries, and notions of density, design, and function can be obtained for careful analysis by utilizing radiography. Although x-ray diagnostics are not truly nondestructive because of their ionizing nature, the additional hazard to the device being inspected is usually negligible. The hazard to personnel is usually very small or can be controlled easily via engineered means. The additional hazard presented by utilizing this diagnostic is overshadowed by its unequaled benefits in understanding the nature of the emergency and other hazards present.

Radiography using low-energy and low-flux output is the primary method of choice. It is safer to personnel, provides higher contrast imaging for low-density materials, is cheaper to implement, is lighter in weight, and is smaller in size. If this low-energy radiography is unable to penetrate the material present, then higher energy options are considered. These options can range up to 7.5 MeV peak generators, and—although less ideal from a safety and image-quality standpoint—they can often be the only choice for providing any image at all, especially for industrial applications in which the materials used are often thicker and denser. These higher-energy generators also tend to have much higher fluxes than the low-energy ones, thereby increasing dose safety concerns for personnel.

2.2 EMERGENCY RESPONSE EXAMPLES

To better understand the types of emergency situations that might require radiography, some examples are listed below. The list is only a sampling of the types of emergencies and does not go into detail about historical references. It is provided to show the broad depth of the application of x-ray diagnostics.

- Hazardous item transport accidents
- Pipeline rupture
- Radioactive containment failure
- Unexploded ordnance
- Items of nefarious intent
- Hazardous item smuggling

2.3 OPERATIONS

Attention is often paid to the technical specifications of the diagnostic equipment—such as energy, power, or detector sensitivity—but in the field, other factors must be considered. Environment, logistics, regulations, and personnel management can be key considerations in the operational flow and can even affect equipment selection.

One issue is that the equipment must be shipped to the site. Commercial shipping regulations must be considered, depending on any hazards the diagnostic equipment might have. Almost everything has a lithium-ion battery, which constitutes a shipping hazard. Logistics around the drop off and pick up of equipment at the site must also be considered. Emergency response teams often, but not always, bring their own equipment to the site on their own vehicles. Different teams have different pallets of equipment based on transportation method (plane, truck, helicopter, parachute). Weather delays and difficult terrain can also pose a barrier to getting the equipment on site.

Another significant logistic consideration is power for the equipment. If shore power is unavailable, then batteries or electrical generators may be needed. Electrical generators require fuel, which creates a new hazard. If the equipment electrical components do not match the local grid, then converters will be needed. Some equipment must be maintained at a calibrated temperature. These items will require constant power or a chemical cooling agent, which introduces new hazards. Any extra equipment needed to support the diagnostic equipment takes up space, weight, and cost on the response pallet. Some other diagnostic equipment will often be displaced by new incoming equipment, and the benefit of the new equipment must be greater than what is lost to justify the change.

Working conditions for personnel, including time frame for the work and provision of food and shelter, must also be considered. The environment surrounding the emergency is often hazardous. Chemical, radiation, electrical, confined space, water, and fall hazards may need to be addressed. These unique conditions might require specialized personal protective equipment or special protection for the diagnostic equipment. Remote rigging devices or choreographed operations to reduce exposure time might be needed. If radiation or toxicity are present, or if the site is under water, then time on target becomes a critical factor. The equipment or personnel may have to be lowered in place or carried while climbing, limiting the volume or weight of equipment that can be used.

The local populace may dictate the scope or pace of operations. Local residents may be concerned if the team introduces new hazards with their diagnostic equipment or if schools or public spaces are nearby. Personnel must evaluate whether the environment is permissive or whether the people might interfere. Local regulations and laws may prohibit some activities and will often only be enforced after the fact. Politics may play a role in what equipment can be utilized to mitigate the emergency.

2.4 EXPERTISE

Generally, the best technology available should be used when addressing an emergency situation. Availability often comes at the price of higher sophistication. Current diagnostic capabilities require specialized training and, in some cases, teams of scientists to advise on the techniques and on data analysis. When considering new equipment, preference is given to equipment that is easy to use and understand in the field. However, if the benefit is great enough, then support structures exist to guide the use of highly complex equipment and techniques.

2.5 CURRENT FIELDED TECHNOLOGY

Low-energy x-ray is the preferred diagnostic. This tool comes in the form of generators that weigh less than 20 lb and detectors that weigh less than 10 lb. They can usually image large objects with the aid of custom fixturing tools. They are usually battery operated and are considered rugged and highly mobile. Some versions are portable but have small fields of view (can only image small areas at a time). They can take longer to image larger objects but can be taken into more limited spaces. Some field crews (generally oil pipeline) still use isotopes in heavy shielded containers, but this practice has fallen out of favor because of the hazards inherent with this method. The low-energy generators usually have a radiation area less than 100 ft, and most exposures do not last more than 10 s.

For dense or thick objects, a high-energy generator or isotope is used (again isotopes are not used much in emergency response). The generators usually fall into one of two categories, either a betatron style or linac style. A betatron creates acceleration via electromagnetic fields and circular electron orbits, whereas a linac uses a linear path that employs staged energy boosts to the electrons. Normally they are designed or tuned to energies above 1 MeV peak. For field purposes, they do not usually go above 7.5 MeV because activation products can start to be an issue. Because high-energy photons tend to scatter as their primary mode of material interaction, these units usually come with heavy collimators to limit the beam. The radiation areas for these devices are usually measured in the thousands of feet. The exposures do not usually last more than 60 s.

Most detectors are thin-film transistor-based photodiodes (amorphous silicon) with gadolinium oxysulfide scintillators, known as digital flat panels. The largest field-of-view detectors commonly available have pixel sizes that range from 100 μm to 150 μm. They are usually slow compared with heavier, more expensive, lab-based models with readout times in the seconds. In the field, this speed is not a problem because the exposure times are usually several seconds to 1 min.

2.6 IMPROVEMENTS

The low-energy systems are fast and reliable and are almost all pulsed in nature, but the detectors are not typically built to synchronize with the x-ray generator pulses. They take good images, but the signal-to-noise ratio (SNR) could be drastically improved by removing the detector dead time caused by lack of pulse syncing.

The high-energy systems are powerful enough for field radiography needs but are very heavy and power hungry. They weigh in the hundreds of pounds and usually need a 30 A circuit to run. Many of the parts for these systems are made in a variety of different countries. Ideally these systems would be reduced in size, weight, and power consumption while sourcing all their parts domestically. The same detectors that work well with low-energy systems are very inefficient (>1%) for high-energy systems. Therefore, image phosphor plates are sometimes still used because intensifier plates can be easily adapted for better imaging. Furthermore, these image phosphors do not suffer the dead-time penalties found with unsynchronized digital flat panels.

The largest field-of-view detectors commonly deployed have an active imaging area of 14 × 17 in. Taking an image of a large object requires moving the detector to multiple locations behind the object and collecting multiple exposures. This process can be automated, but available automatic methods have limitations. Therefore, imaging a large object is often done by hand and requires manual data stitching after image collection.

In addition to collecting intensity information, gathering the phase information or photon energy could improve the data fidelity. This process could also benefit other modalities such as neutron imaging or lower frequency photon imaging below the x-ray/gamma-ray spectrum.

3. RADIOGRAPHY STANDARDS AND TEST OBJECTS

Nerine Cherepy, Lawrence Livermore National Laboratory
Phil Kerr, Lawrence Livermore National Laboratory
Alex Leatherland, Atomic Weapons Establishment

3.1 INTRODUCTION

To evaluate the performance of an imaging system, compare the capabilities of different systems, or compare the same system in different adverse scenarios, common test objects and standards are required. Standards and test objects provide a common reference for developers and users to understand the performance of different radiography systems and provide a way to monitor performance of these systems over their operational lifetime. Here, an *imaging system* is defined as a source of particles (e.g., neutrons or x-rays) and a position-sensitive detector for transmission imaging. The Workshop on Radiographic Imaging and Applications (WORIA) Radiography Standards Session discussed concepts behind standards, the currently available standards, and gaps and weaknesses in the community's approach to defining standards. These concepts are presented below. The goals for the session were to begin developing the following:

1. Standards: Objects and methods with community-agreed-upon metrics for comparison of imaging systems. Radiography standards are typically defined by institutions such as International Organization for Standardization (ISO) or American National Standards Institute (ANSI). Physical standards in radiography are typically objects used to calibrate imaging systems using a well defined measurement method.
2. Test objects: Common objects used in imaging such as those with known defects, material compositions, and/or dimensional properties to test imaging systems. The variety of imaging applications and performance priorities challenge the goal of constructing universal test objects. Test objects are therefore generally purpose-built for each system and application and are not defined by a standards organization.
3. Benchmark Datasets: Validated datasets, based on either experimental or simulated data, that can be used to develop and evaluate algorithms.
4. Validated Forward-Projection Models: Generally, software tools used to predict or simulate an imaging result starting with a known imaging system and object geometry. These models can be used to create realistic synthetic data for various radiography systems, standards, and test objects.

Radiography standards span from relatively simple simple objects and measurement procedures, usually composed of just one or two materials and focused on understanding primary characteristics of radiography systems, to more complicated object and procedures that are constructed to more closely represent an object and measurement procedure that would be encountered in a field scenario. Simple standards typically focus on understanding system performance on characteristics such as image resolution, contrast/detectability, and ability to identify materials and can be applied to a wide variety of systems. Other standards are constructed to more closely represent an object and measurement procedure that would be encountered in a specific field scenario. These standards are less generalizable but provide valuable information on how specific systems may work in well defined field scenarios. The objects used in these standards are typically composed of more than one material—possibly layered or arranged in other more complicated configurations—and are meant to be used to assess the ability of radiography systems to measure properties of real-world objects.

Similar to standards, radiography test objects can span from simple to more complicated geometries and are typically developed for a specific application and are not rigorously defined by a standards organization. These objects are still valuable, and the development of community-driven test objects that are well defined and understood help with evaluating system performance.

Validated forward-projection models are needed by the community to create datasets to develop radiography algorithms and to optimize radiography systems. Forward-projection models are commonly used in the design of radiography systems and can be used to predict how such a system will work in real-world conditions. Unfortunately, many of the Monte Carlo radiation transport codes have not been sufficiently validated for this application, and no common framework exists.

High-quality datasets are also needed to develop the next generation of image-processing algorithms and to compare the performance of these algorithms using a common benchmark. These datasets can be data collected from a real radiography system, data from validated simulations, or a combination of the two. The data complexity can vary depending on the purpose of the dataset.

The motivation for standards is twofold: (1) establish a common set of resources in objects, methods, and data to test and enhance field radiography techniques and (2) adopt common nomenclature to streamline and clarify communications within the community. For either of these commonalities to exist, common definitions must be established and adopted as a reference.

3.2 CURRENT STATE OF THE ART

A prevalent source of imaging standards is in the medical imaging/radiology field. Common standards in the United States are defined by the National Electrical Manufacturers Association (NEMA), the International Electrotechnical Commission in Switzerland, and the Deutsches Institut für Normung in Germany. These standards define evaluation of image quality, resolution, low-contrast detectability, and patient dose. For example, a literature review of standards by A. Schreiner-Karoussou [66] indicated that in order to evaluate the image quality of computed radiography (CR) and direct digital radiography (DDR) x-ray systems, the following parameters are measured:

- Homogeneity
- Dynamic range
- Contrast resolution
- Threshold contrast detail detectability
- Limiting spatial resolution
- Geometric distortion

Schreiner-Karoussou also recommended identifying artifacts, measuring patient entrance dose, and noting the method for measuring exposures.

In addition to officially recognized standards in the medical community, many informal objects and methods are used in various industries that perform imaging. These informal objects and methods are often purpose-built and may lack universal application. Some common general features shown in Figure 1 are linear or radial line pairs or slots made of various materials and with varying pitch, step wedges, wire gauges, ball phantoms, and rectangular, cylindrical, or spherical assemblies with multiple layers of several materials that can be varied to challenge the imaging systems in different ways.

The following subsections describe current x-ray and neutron standards and test objects.

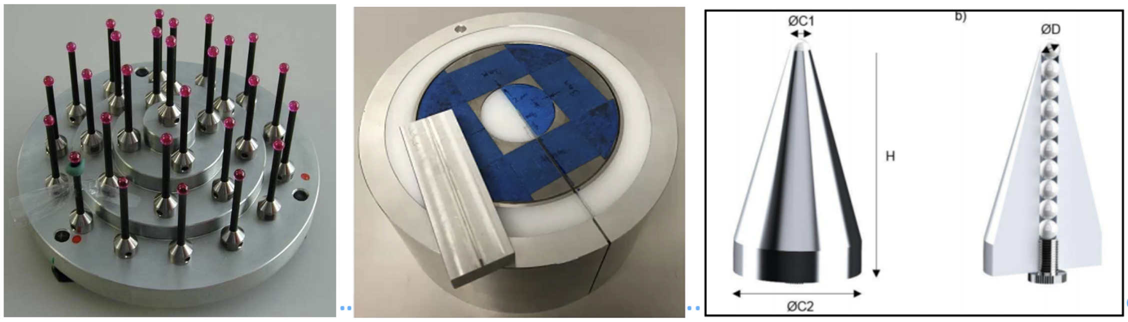


Figure 1. Test objects, from left to right: Styli Forest ball phantom, JH2-KC1, multimaterial cone and ball stack

3.2.1 X-ray Standards and Test Objects

Various physical standards and test objects exist for x-ray imaging, primarily to study image resolution, contrast, and material identification performance and to provide attenuation calibration. However, not all of these standards include measurement procedures. X-rays interact with matter in one of three ways: photoelectric absorption, Compton scattering, and pair production. The interaction probabilities for each scale with the atomic number and the density of the object. Furthermore, the scattered electrons can reemit radiation in the form of bremsstrahlung. Consequently, different materials are better than others to study low- to high-energy photon interactions. Lower Z materials (e.g., steel) are better for studying lower energy (keV) x-rays and higher Z materials (e.g., tungsten) are better at studying higher energy (MeV) x-rays. Using multiple materials can be beneficial for studying x-ray sources with broad emission-energy spectra, allowing the study of attenuation across a wide energy range. These standards are listed in Table 1 and come from various international standards organizations and/or from US/UK laboratories.

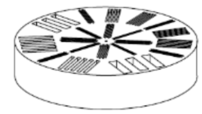
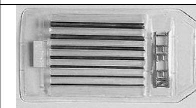
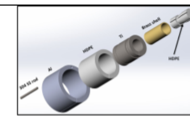
Numerous standards and test objects for high-energy x-ray radiography have been or are being developed. In particular, research is ongoing for industrial high-energy x-ray radiography. Standards for metrology of additively manufactured parts is also developing, noting that transmission and computed tomography (CT) imaging techniques for additive manufacturing (AM) metrology is a very active research area. However, no common community-agreed-upon test objects have been developed for field-radiography applications. This area of active research will likely result in some common and some application-specific standards.

3.2.2 Neutron Standards and Test Objects

Neutrons have no charge and primarily interact with atomic nuclei via elastic and inelastic scattering. The probability that an interaction occurs is described by the neutron cross section and changes to neutron energy and to the atomic nucleus. Generally, thermal neutrons interact more readily with light nuclei, whereas fast neutrons can penetrate more deeply into these materials. This capability is important for neutron standards. Test objects standards used for thermal neutrons may have different requirements than for fast neutrons.

ASTM International (formerly the American Society for Testing and Materials) (ASTM) has published a few standards for thermal neutron radiography: Thermal Neutron Radiography of Materials (ASTM-E748), Determining Image Quality in Direct Thermal Neutron Radiographic Testing (ASTM-E545), Determining the L/D Ratio of Neutron Radiography Beams (ASTM-E803), and Standard Test Method for Neutron Radiographic Dimensional Measurements (ASTM-E1496) [15, 14, 16, 13]. ASTM-E545 and ASTM-803 contain methods and standard objects for thermal neutron radiography, whereas ASTM-E748 and ASTM-1496 focus on measurement procedures to evaluate radiography systems.

Table 1. Summary of x-ray radiography standards and test objects.

Name	Materials	Applications	Geometry	Size	Photo
Kaleidoscope* test object	Tungsten alloy	Resolution	Cylinder with radial slits	$\varnothing$79 mm $\times$ 13 mm height	
Step sedge standards	Aluminum, steel, brass, and other materials.	Image size and attenuation calibration	Stepped wedge	Various	
Wire gauge standards	Steel, tungsten, and other materials	Resolution	Wire	$\varnothing$0.05–5 mm	
XR05† Test object	Aluminum, HDPE, titanium, brass	Materials discrimination	Concentric cylinders	$\varnothing$4.5 in. $\times$ 4 in. height	
Ball phantom† Test object	Tungsten carbide on aluminum, ruby on carbon fiber	Image registration and alignment	Spheres embedded in or topping low-Z posts	Spheres: $\varnothing$5 mm tungsten carbide/$\varnothing$4 mm ruby. Posts: 20 cm tungsten carbide/22–64 mm ruby	

*Developed by Los Alamos National Laboratory/Atomic Weapons Establishment.

†Developed by Lawrence Livermore National Laboratory.

Unlike x-ray standards, not many common fast neutron standards or test objects exist, and no standards or test objects are defined by any formal standards organization for field radiography. Instead, standards and test objects have been assembled by different research groups to meet their needs. A list of standards and test objects for thermal and fast neutron radiography are described in Table 2.

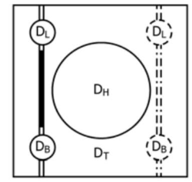
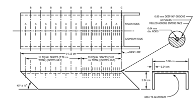
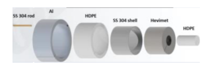
3.2.3 Simulation Standards

Creating the simulation geometry for a radiography system and imaging object of interest can be a large part of the effort of performing radiation transport simulations. Large gross features can be easy to incorporate, but small details in model geometry, which can significantly affect simulation results, can be very time-consuming. Geometry models are typically built "by-hand," using detailed specifications from laboratory measurements and system/object specifications. Furthermore, model validation is typically performed for a specific measurement scenario and radiography system, and it may not translate to other applications. For field-radiography applications, no validated simulation standards are agreed upon by the community.

3.2.4 Standard Datasets

The medical imaging community has developed standard datasets to train and evaluate advanced image-processing algorithms, including chest x-ray [54, 77], MRI [2], and CT [6] datasets. For neutron radiography, standard datasets are much less available, mostly owing to the niche use of this modality [58, 52]. No benchmark datasets are currently available for field radiography.

Table 2. Summary of thermal and fast neutron radiography standards and test objects.

Name	Materials	Applications	Geometry	Size	Photo
ASTM-E545 Standard	Polytetrafluoroethylene, boron nitride, lead, cadmium, or gadolinium	Thermal neutron resolution	Block with disks and wires	N/A	
ASTM-E803 Standard	Cadmium and aluminum	Thermal neutron source collimation	Neutron-absorbing rods positioned at various distances from the image plane	2.45 × 14.13 cm	
JH2-KC01 Test object	Tungsten alloy, HDPE	Fast neutron materials discrimination	Concentric cylinders	⌀4 in. × 3 in. height	
PK1 Test object [33]	Tungsten alloy, HDPE	Fast neutron contrast measurement	Tungsten shell with HDPE hollow cylinder	Tungsten: ⌀5 in. × 0.5 in. thick; HDPE: ⌀2 in. × 0.5 in. thick	
Steel plates and ball	Steel	Fast neutron High attenuation tests	Ball and plate	Steel plates: 6 in. thick; Steel ball: ⌀5.7 cm	
HDPE cylinder inside high-Z cylinder	Tungsten alloy, HDPE	Fast neutron resolution	Concentric cylinders	Tungsten alloy: ⌀19.5 cm × 32 cm tall; HDPE: ⌀17 cm × 32 cm tall × 1 in. thick	
AWE image-quality indicators	Bronze, steel, aluminium, Delrin, and tungsten	Fast neutron resolution	Cylindrical	5 cm outer diameter	
LANL modular blocks	Various, including steel, polyethylene, copper	Material identification	Cubes	1 in.^{3}	

3.3 ROAD MAP FOR STANDARDS ADVANCEMENT

Radiography standards and test objects can be improved by consulting a range stakeholders with different requirements, most notably information protection, commercial sensitivity, nonproliferation, and security classification. The expectation is that a set of universal standards and test objects can be developed for field radiography that are shared across a broad range of applications. Other standards will likely be developed for individual applications and vendors such as inspections of public and private infrastructure.

3.3.1 Community Coordination and Organization

Community coordination and organization represents the single largest nontechnical gap for the advancement of imaging standards and test objects. The field-radiography community needs a glossary of terms and references, preferably located on a public website alongside key contact lists at participating laboratories and institutions. This website should also host design information for an open-source library of general objects, with validated forward projections, Monte Carlo N-Particle/Geant4 models, and datasets so they can be replicated as needed. Ideally, the library would include a set of standards for both general and specific uses, this set could also be used to train machine learning algorithms such as convolution neural networks if it contains known noise and acquisition artifacts. Importantly, this library of objects and object data should cover a range of scenarios for each object that could be considered emblematic of key problems for field radiography and tomography.

When information is collated, generality vs. specificity must be considered. Quality control will always be tested against objects specific to an application, general objectives and specific performance metrics will depend on the different scenarios. Although field radiography encompasses many possible scenarios, these scenarios should be condensed into a matrix list of emblematic scenarios and object combinations to create performance metrics (benchmarks) as is done with medical imaging libraries. This matrix list would not be a set of standards initially; instead it would contain test objects that could later become standard if necessary.

Use of standards in field imaging presents a particular challenge for field image magnification and registration standards because, for field radiography, imaging distances and object geometries can vary not only by application but also within the same application. A library of needed validated computational modeling resources was listed in the previous subsection. Validation to the satisfaction of the diverse field-radiography community (even within a single specialization) presents a research challenge. Given the safety and security implications of many applications in field radiography, this would need to be fully peer reviewed via a rigorous validation and verification process. Validated forward models would also require comparison against experimental data, which would require data and metadata standards. Defining the test objects that generate the data standards must be underpinned by research priorities.

Validation and standardization of analysis methods and analysis success present another important research challenge for each category of field radiography. Requirements for parameters such as detection and resolution must be defined, as well standard methods of testing these metrics.

3.3.2 Performance Criteria

A field radiography information hub should include a glossary, a repository of community-controlled electronic resources, and explained links to important third-party information and suppliers. Longer term, this hub could contain training information and certification.

After this information hub—including data and reference material to center the community action and research—is created, the next step would be engagement with standards institutes to establish the path to creating new standards appropriate for field radiography. When creating these standards, it is crucial to remember that the myriad applications and problems facing field radiography means that the same performance metrics standards may not be appropriate for every application. Instead, the following recommendations apply:

1. Expand the current standards for imaging calibration to include more imaging techniques such as, but not limited to, phase contrast, multimodal imaging, and single-side imaging.

2. Establish a standard of shielding categories. A significant number of problems faced by field radiography refer to difficult scenarios in which the object is hidden or shielded from detection. Instead of having a matrix of objects and shielding standards, a series of shielding/occlusion standards for testing performance metrics may be better.
3. Create classified set that is available on closed networks for some applications as necessary.

3.3.3 Standard and Test Object Development

The overall goal of radiography standards and test objects is improved understanding and development of imaging systems, which leads to improved precision and speed, and maximum safety and effectiveness for users. For field inspection systems, the goals include improved reliability, speed, resolution, contrast, and size, weight, and power (SWAP). Standards in imaging techniques and qualification of new equipment provide users from wide geographical locations with common, peer-reviewed imaging goals, resulting in enhanced, compatible, and reliable capabilities. In particular, research is needed to develop standards, test objects, forward-projection models, and datasets to quantify the following system performance characteristics.

Improved feature extraction: Improved resolution enables identification of progressively smaller features or defects in imaging. Standards in techniques and objects allow the community to work with a common set of tools to compare and jointly improve imaging systems.

Improved shape identification: Resolution is also important for shape identification. Contrast is important when the subject being imaged contains materials with a wide range of densities. Higher intensity sources can help with contrast, and some research is ongoing toward producing higher output x-ray machines with reduced weight. Fast neutron transmission has a lower dependence on material Z than x-rays and can also help improve contrast. This improvement may come at the cost of lower resolution because fast neutron imaging is currently the only practical choice for field neutron radiography. Neutron imaging screens must be relatively thick compared with x-ray screens owing to the lower material interaction of neutrons, thus resulting in lower resolution.

Material identification: Currently, material identification is one of the more challenging and active areas in imaging research. Multiple techniques are being pursued, including dual-energy x-ray, backscatter x-ray, dual-energy neutron, dual x-ray and neutron, and ultrasound. Active neutron interrogation, especially when combined with associated particle imaging (API), can provide material identification. Neutrons can provide elemental and isotopic identification as opposed to chemical identification.

Model validation and verification: Iteration between modeling and measurement is a vital combination for development of technology. Each component can identify problems or weaknesses in the other. Models are limited in value until they agree with measurements and vise versa. Model validation is important in developing each of the aforementioned areas.

3.4 CONCLUSIONS

Although some imaging fields have well established standards and test objects for testing and qualifying imaging systems, many more imaging fields are developing and need standardized test objects and testing techniques. Other applications have the same safety constraints for end users but may not have the same constraints on the subject of the imaging. These circumstances may explain the less rigorous approach to standards and the wide range of test objects and techniques across other fields and even within similar applications.

Coordination, collaboration, and communication in a peer-review process are critical to the development of standards. A glossary of common definitions and descriptions of techniques is important for communication between research groups and for reproducibility of results between groups. A common set of standard test objects is also needed, at least within common applications research. Some commonality of test objects and models may be possible across applications. Other sets may be more limited and restricted as business proprietary or classified.

Standards and test objects offer a method to improve precision and speed and to maximize imaging systems' safety and effectiveness. Improved resolution, speed, material identification, and multimaterial contrast in imaging are challenges that are being actively researched. Coupling test-object models with measurements is critical to this research. Validated models and codes can be shared and can allow for quickly testing modifications to test objects. These modifications can be used in the next iteration of imaging tests conducted for the optimization of an imaging system.

Standards and test objects cover a range of concepts, from objects designed for specific tests, nomenclature, and training, to methods of image acquisition and processing for specific applications. The latter are notably prevalent in medical imaging. In terms of physical objects, the standards available to the field-radiography community primarily focus on the quality of imaging for facility-based imaging quality, and field-imaging-specific object needs are addressed by more informal imaging test objects and imaging quality objects at different institutions. For most imaging methods, addressing this deficit is less a problem of driving new research and development, which is happening already, and is more an issue of community engagement. This engagement is crucial not only internally to agree upon required measurements for object standards but also externally with standards institutions to formalize those choices.

The standards of training, nomenclature, and methods represent a less concrete but important challenge. Here from observations at WORIA, the primary weaknesses appear to be a lack of a common repository of knowledge to refer to or derive common training and expertise from. Although the knowledge and expertise of all the relevant areas are clearly present within the community, the specialisms required for field radiography are broad and multidisciplinary, and forming standards of knowledge will be incredibly difficult without common information resources. Good examples of these resources are the International Atomic Energy Agency's Neutron Imaging E-Learning course, the training resources provided by the Collaborative Computational Project in Tomographic Imaging, the user community training by Laserlab Europe, and Radiopaedia. Creating a common repository would require a stakeholder institution to take ownership of and host an online resource. This resource would have minimal costs compared with the benefits a common knowledge and training repository would provide.

4. DETECTOR MATERIALS

Nerine Cherepy, Lawerence Livermore National Laboratory
Patrick Feng, Sandia National Laboratory
Mercouri Kanatzidis, Argonne National Laboratory

4.1 INTRODUCTION

High-energy (MeV) x-ray and neutron radiography utilize detectors based on scintillator and semiconductor technologies to spatially resolve thick and/or dense item(s) of interest. Specific material developments, detector structures, and system-level improvements are required to meet the need for high-efficiency and high-spatial-resolution radiographic imaging [79]. This section focuses on three key topic areas aimed at meeting these needs:

1. Imaging detector materials for MeV x-ray and fast neutron radiographic imaging applications
2. Thick pixelated detector structures for high efficiency and improved spatial resolution
3. Co-optimizing the detector material properties and structures with optical transport/photodetector characteristics

This approach addresses the limitations of existing detectors that are generally only suitable for low-energy x-rays and neutrons.

4.2 RELEVANT MEASUREMENT TECHNIQUES

The detection materials considered here have the potential to be used in field measurements that employ any of the following measurement techniques.

High-energy transmission radiography refers to imaging techniques that measure and record changes in a high-energy particle beam (e.g., x-rays, neutrons) resulting from interaction with an object of interest. Transmission radiography requires the incident particles to pass through an object to a detector located on the far side of the object. Variations of this technique may be applied. One example comprises dual-energy x-ray transmission radiography, which can provide imaging and information about the atomic number of the objects under examination.

Backscatter imaging detects the scattered radiation that reflects from the target and requires access to only one side of the object of interest. Backscatter imaging has been employed for both x-ray and neutron sources and involves the detection of scattered Compton x-rays or thermal neutrons, respectively. This technique can provide material identification by detecting variations in the scattering cross sections of different materials (e.g., elemental differences in electron density for x-ray backscatter imaging). Backscatter imaging is difficult or may be untenable for imaging materials that have higher atomic numbers [67].

Associated particle imaging is an active neutron probe technique that provides a 3D image with elemental composition of the material under interrogation. API uses the direction and time correlations between fast neutrons and alpha particles produced in an accelerator via the deuterium–tritium (DT) reaction. This technique constitutes electronic collimation of the neutron beam from the DT generator to reject the majority of scattering from the transmission image to maintain excellent contrast compared with integrating detectors. Detection of the alpha particles with a position-sensitive detector produces the direction and time of emission of the associated neutron. The neutron may then be directly detected in transmission mode, or it may proceed to interact with nuclei in the object of interest to produce characteristic gamma-rays (induced-reaction imaging). The position and time of interaction of these neutron-induced events may be used to provide an image and/or elemental composition of the target.

These techniques typically require different qualities from detection materials to be successful, such as fast timing, high detection efficiency at high energies, and/or high spatial resolution. These qualities are discussed further in the following subsections.

4.3 BACKGROUND AND STATE-OF-THE ART: RADIOGRAPHY DETECTION MATERIALS

X-ray radiography enjoys widespread use in medical and industrial applications. Most contemporary radiography detectors are based on storage of phosphor-based image plates (CR) or semiconductor detectors (dynamic range (DR)). Typical CR image plates are based on thin phosphor coatings of BaFBr:Eu^{2+} or CsBr:Eu^{2+}. DR detectors are based on either direct detection in amorphous silicon (a-Si) or amorphous selenium (a-Se) thin-film transistor (TFT) panels or indirect detection in scintillators coupled to a-Si panels. Scintillators for indirect detection generally comprise Gd_2O_2S phosphor films or uniaxially-grown CsI(Tl) microcrystals. The rationale for these choices accounts for several factors, including the following:

- Interaction efficiency: intended x-ray energies and radiation cross-section of detector materials
- Spatial resolution and signal-to-noise (modulation transfer function (MTF))
- Radiation hardness at intended dose rates
- Cost

Generally, detector panels have been widely optimized for low- to medium-energy x-rays (e.g., <500 keV) for different reasons depending on the application. In medical imaging, low-energy x-rays are preferred because of the low atomic number of bone and biological tissues. In this case, the interaction physics of low-energy x-rays facilitate detection. For example, a thin scintillator layer or phosphor-coated light guide is sufficient to stop the majority of low-energy x-rays, allowing for high spatial resolution and little to no radiation damage to the underlying photodetector (e.g., an a-Si TFT panel).

In industrial applications, higher energy x-rays are generally desired to image thicker and/or higher atomic number materials. For this reason, isotopic ^{192}Ir sources and portable x-ray generators of up to 400 keV are often used because of their widespread availability. Higher-energy (MeV) x-ray sources such as betatrons or linacs are superior for imaging dense or thick objects but are less widely used because of limitations in their size, weight, and cost. Radiography detectors for higher energy x-rays also become more challenging to design because these photons penetrate deeper into the material. For example, thicker scintillation coatings increase the detection efficiency but reduce the radiographic spatial resolution owing to light-scattering and spreading effects. Radiation damage to the photodetector material also becomes a more significant concern because the scintillator, which is thin compared with the attenuation length of incident MeV-scale x-rays, provides incomplete radiation shielding.

Neutron radiography was developed to image thick and/or high-Z materials, owing to the penetrating nature of neutrons in heavy elements and relatively low dependence of fast neutron interaction cross sections upon the Z number [53].

Thermal neutron radiography is typically achieved by employing thin layers of scintillators that contain elements with high thermal-neutron-capture cross sections. Examples of these detectors include films of LiF-ZnS(Ag) or ^{6}Li doped ZnS phosphors imaged by a lens-coupled charge-coupled device (CCD) camera, GdO_2/BaFBr:Eu storage phosphor image plates, or thin layers of ^{157}Gd deposited directly on a pixelated complementary metal-oxide semiconductor (CMOS) detector [83, 38, 39] These thin (e.g., <500 μm) neutron-capture materials are advantageous for spatial resolution and light transport but disadvantageous for detection efficiency [73]. Consequently, thermal neutron radiography is typically performed at specialized facilities that can provide high neutron fluence and/or long exposure times. (e.g., nuclear reactors, spallation sources, dense plasma focus).

Portable neutron generators that employ deuterium–deuterium (DD) and DT reactions have been/are being developed to support portable fast neutron radiography applications [**williams**, 33]. These generators are discussed further in Section 5.6. DD and DT neutron generators provide 2.45 MeV and 14 MeV fast neutrons, respectively. Consequently, moderating materials are required for the thermal neutron capture detectors mentioned above. Designing a moderator that is not only sufficiently thin to maintain high spatial resolution but also sufficiently thick to effectively moderate the neutron beam is a practical challenge. Simulations by Ma et al. [48] calculated a maximum conversion efficiency of less than 0.4% for a detector based on a phosphor attached to a 2 mm thick HDPE converter. Thicker HDPE layers did not increase the conversion efficiency owing to the self-absorption of recoil protons. This observation indicates that converter-phosphor fast neutron detectors have a fundamentally low efficiency limit. Detectors based on direct fast neutron interactions in organic scintillators can overcome this efficiency limitation, although light-spreading effects in thick detectors typically increase the extent of image blur and degrade the spatial resolution [57].

Associated Particle Imaging is a 3D imaging technique using fast neutrons. It utilizes the direction and time information between the 14 MeV neutron and its associated alpha particle produced by the $T(d,n)^4He$ reaction in a small accelerator or sealed-tube neutron generator. Detection of the alpha particle with a position-sensitive detector provides the direction and time of emission of the neutron. The neutron may then interact directly within a detector or participate in an induced reaction with a target nucleus to produce characteristic gamma-rays. This section focuses on contemporary approaches to improve the detection performance of fast-neutron-sensitive materials and methods to configure/produce the required detector architectures. At present, the most mature API systems are based on detecting neutron-induced gamma-ray signatures using inorganic scintillators (e.g., NaI(Tl), $LaBr_3$) and interaction position reconstruction methods [21]. Significant R&D into direct fast-neutron detection using pulse-shape discrimination (PSD)-capable organic scintillators coupled with pixelated silicon photomultiplier arrays [23].

4.4 PERFORMANCE CRITERIA

4.4.1 Scintillator Material Characteristics

X-Ray Radiography

- X-ray attenuation length: High mass density and Z number are desired to minimize the required scintillator thickness for high efficiency.
- Light output: High light output required (>50,000 photons/MeVee).
- Size: Producible in large areas (30 × 30 cm) and thicknesses (e.g., >0.5 cm).
- Afterglow: Minimize scintillation after radiation exposure.
- Self-absorption: Optical transparency and low optical self-absorption to minimize attenuation and blur.
- Environmental stability: Scintillator must be stable and non-hygroscopic
- Radiation hardness: High radiation hardness required for consistent performance and long panel life. Required level of radiation hardness depends on the system's efficiency and intended use case.
- Mechanical toughness: Rugged materials capable of withstanding the thermal and mechanical shock requirements for field-deployable detectors.
- Refractive index: High refractive index desired for efficient optical transport.

- Cost: Acceptable material and detector fabrication costs.

Fast Neutron Radiography

- Intrinsic neutron detection efficiency: High neutron detection efficiency, as governed by the light yield and linear density of hydrogen in the scintillator.
- Size: Producible in large areas (30 × 30 cm) and thicknesses (>2 cm).
- Integrated dose per image: A combination of detector efficiency and pixel size, the dose required to produce a suitable statistical precision per pixel.
- Light output: High light output exceeding 12,000 photons/MeVee.
- PSD: Efficient PSD required for neutron API.
- Self-absorption: Optical transparency and low optical self-absorption to minimize attenuation and blur.
- Radiation hardness: High radiation hardness required for consistent performance and long panel life. Required level of radiation hardness is dependent on the system's efficiency and intended use case.
- Environmental stability: Scintillator must be stable and insensitive to moisture- and/or temperature-induced degradation.
- Mechanical toughness: Rugged materials capable of withstanding the thermal and mechanical shock requirements for field-deployable detectors.
- Cost: Acceptable material and detector fabrication costs.

4.4.2 System-Level Characteristics

Various quantitative parameters are used to describe imaging systems, including medical and industrial x-ray detectors. A brief description of these metrics is provided below. These parameters also apply to MeV-scale radiography, although comprehensive reports on these properties for high-energy imaging detectors are sparse. Standardized characterization measurements will be required to assess the performance of each candidate detector system.

Spatial resolution (SR) Defined as the full width at half maximum (FWHM) of the line spread function (LSF). The LSF is obtained by differentiating the edge spread function (ESF), which is a histogram of intensity distribution across the image of the test sample edge.

contrast sensitivity (CS) figure-of-merit The contrast sensitivity evaluates the ability to perceive sharp/clear outlines of very small objects and a measure of how much a pattern must vary in contrast to be seen. For two adjacent areas of the same size, it is given by

$$\mathrm{CS} = \frac{I_1 - I_2}{I_1 + I_2} = \frac{2\Delta}{I_1 + I_2} = \frac{\Delta}{I_{\mathrm{av}}}, \tag{1}$$

where I_1 and I_2 are the image intensity in these areas, and Δ is the deviation of signals from the average value $\mathrm{I_{av}}$. Thus, CS should be compared with the relative standard deviation of the image intensity owing to statistical noise in the considered area. As CS << 1, CS is equal to the deviation of ($\Sigma_i\ d_i$), where Σ_i is the macroscopic cross section for beam attenuation, and d_i is the sample size along the beam direction. The CS figure-of-merit is thus given by

$$\mathrm{CS\ FOM} = \frac{1}{\mathrm{CS}}. \tag{2}$$

DR describes the range of x-ray intensities that a detector can differentiate. DR is largely controlled by the characteristics of the photodetector and is related to the bit depth of digital x-ray detectors.

detective quantum efficiency (DQE) measures the combined effects of the image contrast and noise performance and is generally expressed as a function of the spatial frequency. In addition to material properties (such as stopping power and light output), the ability of a detector to convert incoming radiation to countable quanta is also influenced by the ability to, for example, extract scintillation light and convert it to a measurable signal. Therefore, a system-level metric is needed to describe how effectively a radiation-detection system can produce a signal when exposed to a radiation source relative to an ideal detector. This metric is the DQE. A report by the International Electrotechnical Commission (IEC 62220-1) was developed in an effort to standardize methods and algorithms required to measure the DQE of digital x-ray imaging systems [26].

$$\mathrm{DQE} = \frac{I_{\mathrm{out}}/\Delta I_{\mathrm{out}}}{I_{\mathrm{in}}/\Delta I_{\mathrm{in}}}, \tag{3}$$

where I_{in}, I_{out}, ΔI_{in}, and ΔI_{out} are the input and output signals and their standard deviations. To maximize DQE for an imaging system, developers typically maximize I_{out} by optimizing image contrast while minimizing noise ΔI_{out}.

Radiation interaction efficiency describes the ability of the detector to convert incident ionizing radiation into electrical signals in a digital radiographic detector. This response accounts for the physics of ionizing radiation interactions in the detector, as measured by the radiation attenuation length and light output of the scintillator. Key considerations include ionization and recombination phenomena along with the optical photon detection efficiency of the position-sensitive photodetector.

4.5 TECHNICAL GAPS

Some key limitations (technical gaps) that currently prevent the achievement of the required performance and implementation of new types of radiographic imaging detectors are summarized in the following table. Brief statements outline the general path forward to overcome the limitations. This summary is a precursor to the specific required R&D topics and future road map, which are presented in Section 4.5.1.

Table 3. Key limitations (technical gaps) that currently prevent the achievement of the required performance and implementation of new types of radiographic imaging detectors

Requirement	Present technical limitation and need
High sensitivity and efficiency	· Existing detectors provide low detection efficiency for MeV x-rays/neutrons because of the thin scintillator thicknesses that are associated with crystal growth and/or light-transport constraints. Thick detector materials are required that minimize the extent of spatial resolution degradation · X-rays: Need higher-density detector materials with high light output and optically segmented structures. · Neutrons: Existing thermalization-based neutron detectors have a low intrinsic efficiency limit. Need transparent organic scintillators to increase efficiency via greater thickness. Also need higher light output and, in the case of API, more efficient n/γ discrimination. Optically segmented structures will be required to minimize stray light associated with light-spreading effects in thick detectors.
High spatial resolution	· Existing detectors for low-energy x-ray radiography provide high resolution via favorable light transport associated with short optical path lengths. The thicker detectors that are required for MeV-level radiography will require improved light transport to maintain high resolution. Preferred strategies include optical isolation, detector segmentation, and/or optical waveguide structures. · For API neutron detection systems using thick detectors, depth of interaction is needed to reduce the effects of parallax.

Fast readout, high frame rate	· Need short scintillation decay times and low afterglow. Success will also require fast photodetector readout and signal processing for real-time radiography.
Ruggedness Long-term stability	· Need mechanically rugged materials such as ceramics (x-ray radiography) and polymer-reinforced organics (neutron radiography). · Need radiation-hard materials that are also stable toward environmental aging.
Manageable cost	· Need cost-effective and scalable materials that provide a pathway to commercial viability
Consistent performance standards/benchmarking	· Need to establish and implement methodology for the evaluation of detection systems. Requires understanding the respective contributions and combined response of scintillator material, photodetector characteristics, and readout methods.

4.5.1 Synergistic R&D

The imaging detector comprises one aspect of the overall radiography system that includes, at a minimum, the radiation source, detector panel, readout electronics, and analysis algorithms. Consequently, the respective system components must be co-optimized at the system level. Each system component's contribution to the overall system performance and cost must be understood to allocate resources to meet technical and cost requirements. One instance of this system-level optimization involves the interplay between efficiency and spatial resolution. Either factor can be prioritized for each system component. For example, high efficiency can be obtained by adopting a large spot size at the radiation source, small source-to-detector distance, and a thick slab of bulk scintillator. Conversely, high spatial resolution may be achieved by employing a small source spot size, large source-to-detector distance, and thin scintillator or phosphor layer. Improvements in compact, high-flux radiation sources and in thick spatially resolved detectors will relax these existing trade-offs. These system-level decisions define key application specifications such as the required source flux and associated total measurement time.

4.5.2 Required R&D to Bridge Technical Gaps

The following R&D recommendations will help bridge the aforementioned technical gaps.

1. Develop scalable and cost-effective processes to fabricate pixelated detectors from high-stopping-power scintillation materials for MeV x-ray radiography. Approaches include the following:
   - Light-transport structures of high-light-yield and high-stopping-power ceramic scintillators. Light-isolating methods include microstructure formation via laser etching and the use of light-isolation materials between discrete scintillator elements (e.g., gadolinium lutetium oxide) [5].
   - Thick microcapillary array structures filled with inorganic and/or hybrid organic–inorganic scintillators (e.g., solution-grown phenylethylammonium lead bromide) [10].
   - High-Z x-ray grids as a means to optically isolate inorganic scintillator pixels and to provide improved image contrast via antiscatter [9].
   - Improved methods for thick growth/fabrication of microcolumnar scintillator structures for uniaxial light guiding (e.g., improved microcolumnar CsI(Tl) growth/light transport) [64]. Includes templated growth in scaffold structures.
   - System integration and design studies to evaluate practical scintillator/photodetector configurations for field use (e.g., expected system lifetime after accounting for radiation effects/shielding in scintillator and photodetector).

2. Develop scalable and cost-effective processes to fabricate pixelated scintillation materials for MeV fast neutron radiography. Approaches include the following:

    - Structured thermoplastic organic scintillators that provide high light outputs that exceed that of traditional plastic scintillators. Structures include fused optical-fiber plates comprising traditional core-clad scintillator elements, with or without other light transport-assisting components such as extramural absorbers and reflectors. [54, 81].
    - Nanostructured scintillator monoliths for uniaxial light guiding (e.g., nanoguide optical waveguides) [19].
    - Environmentally stable organic scintillators that are resistant to radiation damage at megarad and higher dose levels [40, 51].

3. Develop PSD-capable, pixelated, fast neutron detectors for API. Approaches include the following:

    - Mechanically rugged and environmentally stable organic scintillators that are configurable into coarsely segmented arrays (e.g., 5×5 mm pixel cross sections) [23, 54, 71].
    - Scalable and cost-effective methods for the manufacture of segmented detector arrays.
    - High-performance organic scintillation materials that prioritize light output, coincidence timing resolution, and n/γ discrimination. [3, 80]. Cost–benefit studies to evaluate the effect these characteristics have upon the system performance and cost.

4. Develop standardized detector evaluation and grading metrics. Approaches include the following:

    - Establish uniform criteria for assessing radiographic detector performance (e.g., define standard imaging test objects and procedures, methods for determination of technical metrics [e.g., MTF and DQE]). Adopt accepted standards when possible [26].

5. READOUT ELECTRONICS

Gabriella Carini, Brookhaven National Laboratory
Lorenzo Fabris, Oak Ridge National Laboratory

5.1 INTRODUCTION

Field radiography comprises three main application areas. A common thread for all applications is that their R&D aims toward innovating the state of the art represented by commercial systems, offering the possibility of greatly improving future performance. These R&D efforts are generating concrete improvements, and very desirable future outcomes seem likely. The following areas of improvement were identified:

- Radiography
- Associated Particle Imaging
- Interaction-resolving detectors

The requirements of field radiography emphasize portability, which immediately sets a series of flow-down constraints on all aspects of a system but especially on SWAP. For example, for a system to be portable, a proper power source must be chosen. Wall power is not always available; thus, batteries are often used to power a system. However, the size of a battery cannot be arbitrary: it influences overall size and weight, and it is often limited by safety or commerce laws for what concerns shipping via land or air, especially for batteries based on lithium chemistry, which are, by far, the most desirable type to date. These requirements, coupled with a very high standard for desired performance, make the design of near-field imaging instrumentation not only quite challenging but also very interesting.

5.2 APPLICATIONS

Radiographic applications address the need to identify the content or the composition of objects when the content or the object itself is inaccessible for normal inspection, such as the content of a drum. This inspection is typically accomplished via radiographic means using either high-energy x-rays, gamma-rays, or neutrons. Muons are also employed in a limited number of applications. Except for muons, which are outside the scope of this review, most of the probing radiation is generated by radioactive sources or by radiation-generating devices (RGDs). During direct imaging, the radiation source and the detector are typically placed on opposite sides of the object to be inspected. In some instances, the detector is placed at an angle that is ≤90° from the source to avoid direct irradiation. In this case, the information is contained in the radiation that is scattered from the object back into the detector. The readout electronics are basically the same in either arrangement. In addition to the requirements mentioned above, other requirements for these type of systems are spatial resolution to achieve image detail, panel size, typically of the order of 1,000 cm^2, and in some instances, timing on the order of 100 ps FWHM.

5.3 COMMERCIAL STATE OF THE ART

The detectors in radiographic systems either directly convert incident ionizing radiation to charge in a semiconductor or indirectly convert ionizing radiation first to visible light in a scintillator and then to charge in a photosensor. The conversion in the photosensor may be performed with approximately unit gain, such as in a photodiode array, CCD, or CMOS sensor, or with high gain, such as in photomultiplier tubes (PMTs), silicon photomultipliers (SiPMs) or other single-photon avalanche diode (SPAD) arrays, or image intensifiers combined with photosensors.

The most common digital radiographic systems consist of a thin scintillator screen combined with a photodiode array whose integrated charge is digitized for each pixel to determine the image. This integrating approach enables large-area panels with low cost per area that require relatively simple readouts. Given the nature of the detection, these readouts do not have to offer particularly fast timing but achieve excellent spatial resolution of the order of 100 µm. They are commercially available in many sizes, from panels to industrial setups, and address several applications, including conventional medical x-rays. Some examples of imaging panels and images generated from commercial radiographic imaging systems are given in Figure 2.

Figure 2. Examples of images generated from commercial x-ray radiographic systems and panels used to make those images. The left figure shows an image generated by VJTechologies' Veda HE industrial system [76]. The center image shows a family of radiographic panels produced by Scanna [47], while the rightmost image is a radiograph obtained by a NOVO Systems detector [46].

In this approach, spatial resolution is limited by the spread of light in the scintillator. Sensitivity is limited by a combination of factors, including the noise floor of roughly 1,000 electrons for silicon and a dark current typically less than 1 pA/mm^2.

For integrating detectors, imaging becomes challenging when the integrated charge from signal is smaller than the integrated charge from dark current. This situation occurs for neutron measurements performed using presently available portable neutron sources because the signal strength induced by source neutrons is low compared with the detector dark current. For instance, Kerr et al. report measurements performed with a portable DT neutron generator that has an output of 5.9×10^8 n/s and a Varex Imaging XRD 1621 digital imaging panel with a 2.4 mm thick scintillator sheet composed of polypropylene with 30% ZnS(Cu) [33]. The neutron flux 60 cm from the source corresponds to 20.2 neutrons per second per pixel (0.4×0.4 mm) in the detector. These neutrons result in 0.85 signal counts per pixel per second for an unattenuated portion of the image, approximately two orders of magnitude smaller than the 94 counts per pixel per second from dark current. The true image can be extracted albeit with difficulty.

This situation can also occur for x-ray measurements of sufficiently attenuating objects. High-energy (3–15 MeV) x-rays have low efficiency for typical digital panels (~0.5%). When combined with substantial attenuation, the measured signal can be similar to dark current.

In both these instances, the SNR could be substantially improved when using pulsed sources (portable high-energy x-ray sources are necessarily pulsed). This improvement can be achieved by developing detector readout that enables separate accumulations of signal during the interrogating source pulse and dark current between pulses. This capability would enable both reduction of dark current in the signal image and accurate determination of the dark current for every pixel of the panel during the measurement, thereby enabling the most accurate subtraction possible.

A second class of detectors, pulse-counting detectors, can count individual radiation interactions. Pulse-counting x-ray detectors hold promise for drastically increasing the SNR for high-energy radiography by eliminating low-energy downscatter from images and eliminating counts out of time with the interrogating x-ray pulse. The resulting improvement can be used to minimize the dose required to produce images. Pulse-counting detectors can also enable material identification using the relative intensity recorded in different energy bins. Additionally, pulse-counting detectors can attain resolution higher than that achievable by integration because the event location can be determined more accurately by reconstructing either the center of mass of the interaction within the scintillator or the vertex of a charged-particle track.

The development of currently available systems has been driven largely by the medical imaging community, where several examples of imagers can be found. However, their application to field radiography is less mature than integrating detectors. Only a handful of photon-counting imaging detectors are available commercially. They generally offer smaller footprints (~100 cm^2) and are based on semiconductor detectors. Figure 3 shows an example of such systems. The readout electronics for these systems are more complex than those used in the integrating detectors because each detected photon in each detector pixel must be characterized in terms of energy, position, and often timing. By contrast, the information of interest for integrating detectors is the sum of the events collected by a pixel in a given time interval. Such electronics are often implemented using application-specific integrated circuits (ASICs), which is currently the only solution that allows the integration of complex functions within a small footprint. These detectors also are designed to detect x-rays.

Figure 3. Varex DC-THORE.HE features a 412 × 25 mm active area with 100 μm resolution. Specifications available at [11].

Other commercially available devices designed for a wider range of applications may also be of interest for field radiography. One such device, Amsterdam Scientific Instruments' TPX3Cam is a general-purpose photon-counting converter that may be used for fast light readout [55]. The device has been used to perform thermal neutron imaging by coupling it to a neutron-sensitive scintillator screen via a lens and image intensifier. The intensifier's gain is needed to make individual photons from the scintillator screen visible to the device. The detector system records events at rates up to 80 million counts/s with timing on the order of 1.5 ns. Event-mode data acquisition has be shown to increase the system's resolution by a factor of three by reconstructing the center of mass of neutron interactions [43]. It has also been shown to increase the SNR in images by a factor of seven by eliminating dark counts. This device is based on an ASIC readout [4]. Similar devices based on the same ASIC are available from other vendors.

The robust medical and industrial x-ray inspection industry is expected to continue to develop these techniques. In this context, the role of National Nuclear Security Administration (NNSA) investment should be targeted. Potential areas of investment include robust evaluation of the latest commercially available technologies and judicious investment in emerging technologies. For example, a robust laboratory evaluation of the efficacy—including cost, power and data rate—of commercial spectral pulse-counting x-ray detectors for high-energy radiography using pertinent pulsed x-ray sources would delineate the potential for improvement using this technology. Furthermore, the present solutions require semiconductor converters, but the possibility of using a scintillator screen coupled to a photodiode array can also be evaluated for use with high-energy x-rays. Likewise, the development and evaluation of an emerging material such as a lead halide perovskite semiconductor can be accelerated by support of pairing the material with the Timepix4 (or similar) ASIC readout. This pairing would also ensure relevant applications of the newly developed readout ASIC.

5.3.1 Current R&D

Current R&D focuses on enabling the capability for penetrating imaging of dense objects (or objects that are shielded by dense materials) with superior spatial resolution and contrast for materials. Although commercial systems are extremely capable, they are typically optimized for lower-energy (hundreds of keV) x-ray imaging. Because achieving the desired penetration of dense objects requires the use of high-energy x-rays or fast neutrons, detecting the interrogating radiation with sufficient efficiency to achieve favorable SNR with little transmitted signal requires thick detectors. Instrumenting thick detectors while preserving spatial resolution involves several challenges. Thick detectors contribute to reduced spatial resolution via parallax when the incidence of radiation on the detector is not normal to the detector's front surface, multiple interactions occur within the detector, and, for indirect detection using a scintillator, light spreads in the scintillator before it is detected by the photosensor.

For neutron imaging, thick detectors typically employ an active volume composed of an organic scintillator. However, for portable sources, the amount of scintillation light generated by the available neutron flux is small compared with dark current in integrating detectors. Consequently, neutron imaging substantially profits from detectors that have conversion gain. With sufficient gain, pulse counting is possible. Implementation of the appropriate pulse-counting readout enables the possibility of a range of enhanced capabilities:

- Improvement in image SNR by eliminating the contribution of dark current.
- Recovery of spatial resolution lost to light spread in the detector by determining the center of mass of the detected scintillation light from each interaction. In the best possible embodiment, spatial resolution lost to the range of the recoiling protons in the scintillator can be recovered by identifying the vertex of proton recoil tracks.
- Recovery of spatial resolution lost to parallax by determining the depth of interaction, inferred from either the time or the position distribution of scintillation light on the photosensor.
- Recovery of spatial resolution lost to multiple interactions in neutron imaging by determining the position of first interaction, inferred from the time and position distribution of scintillation light on the photosensor.
- Improvement in image SNR in neutron imaging by eliminating x-ray and gamma-ray counts identified by PSD in an appropriate scintillator (neutron detectors are typically sensitive to x-rays and gamma-rays in addition to fast neutrons).
- Improvement in image contrast and SNR by selecting events with larger deposited energy to enhance the fraction of true transmission.

Semiconductors such as CdZnTe (CZT) are expensive. They also suffer from charge buildup caused by electron trapping owing to defects in the detector. This issue can pose a problem for the rate of energy deposition from high-energy radiography using substantial (centimeter) detector thicknesses.

Targeted R&D has been undertaken by many institutions. Much of the focus is on developing fast neutrons as the probing radiation, and a component of research focuses on improving the readout electronics over commercial solutions.

One promising technique for field neutron radiography is API. This technique uses 14.1 MeV neutrons produced by the d + t → α + n reaction, where the time and direction of interrogating neutrons is determined by detection of the associated alpha particle. The specificity of coincidence between the detected alpha particle and emitted neutron enables transmission imaging with excellent contrast with a modest source ($O(10^8)$ neutrons per second) and no physical collimation. The requirement for coincidence and the limitation by chance coincidences drives the requirements for fast timing.

Prototype pulse-counting fast neutron imaging systems have been assembled and demonstrated by Oak Ridge National Laboratory (ORNL). These systems achieve high efficiency by employing thick, coarsely segmented (centimeter resolution) pixel arrays of organic scintillator and sufficient gain for pulse counting using PMT readout. To minimize development time, the PMT front end is read by a commercial back end. The resulting imaging panel shown in Figure 4 achieves nanosecond FWHM timing resolution, discriminates neutron and gamma-ray pulse shapes, and requires less than 100 W for an approximately 1,000 cm^2 active area.

Present effort is focused on developing pulse-counting solid-state readout using analog SPAD arrays (SiPMs) or digital SPAD arrays (photon-to-digital converters (PDCs)). Solid-state readout is desired as a solution that is more rugged than PMTs, does not require high voltage, and is sufficiently low in power for field use. It can also provide a solution that can scale to large areas and be sufficiently capable to resolve millimeter-scale pixels and multiple interactions in the detector separated by more than a centimeter.

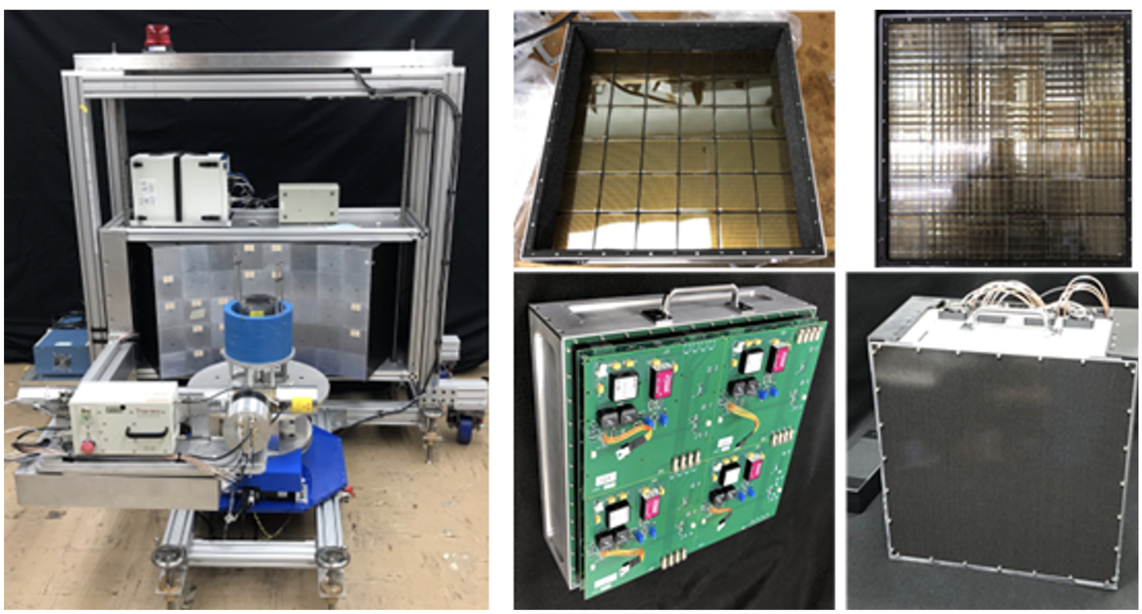


Figure 4. Neutron radiographic system developed by ORNL. (left) A traditional gantry-based system. (right) For comparison, 1,000 cm^2-class imaging panels.

Brookhaven National Laboratory (BNL) is developing other systems based on semiconductor detectors such as CZT, TlBr, Ge, and others. Such systems cannot detect neutrons but offer the opportunity to create images with high-resolution spectral content (1% FWHM resolution) for x-rays and gamma-rays. The detectors rely on the combination of sensors with different geometries equipped with dedicated low-power readout electronics built around ASICs and field-programmable gate array (FPGA) readouts. A typical CZT configuration uses bar-shaped position-sensitive virtual Frisch-grid (VFG) detectors recently developed for photon energies of 0.2–10 MeV that provide position resolution of 0.1–0.5 mm along each of three axes and energy resolution of about 1%, depending on the incident photon energy (Figure 5). The drift-bar approach allows the use of poorer quality CZT detectors, significantly increasing the yield of acceptable detectors and making this technology an efficient and economically viable choice to fill a given volume of detector area with less dead space and reasonable integration complexity. Different approaches using larger crystals with pixelated geometries have been developed and are the focus of R&D efforts in other laboratories (e.g., University of Michigan).

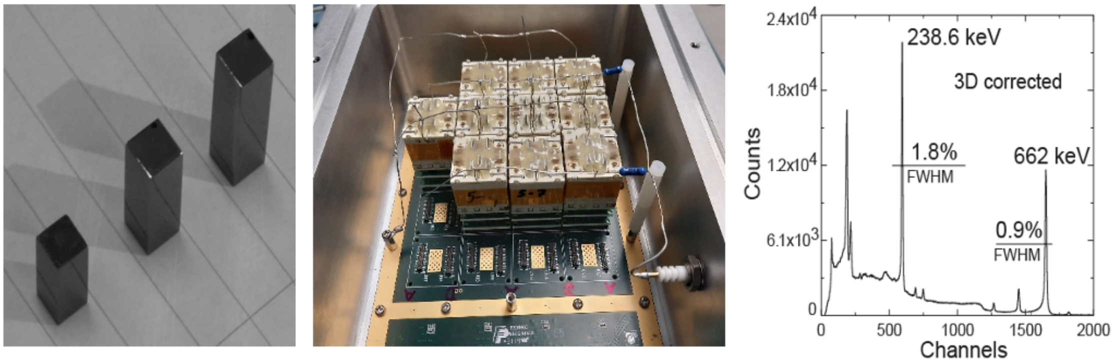


Figure 5. BNL's virtual Frisch-grid CZT detectors with integrated ASIC readout.

From the instrumentation perspective, the different detector technologies presented have many important commonalities. The need for charateristics such as faster than nanosecond timing, high spatial resolution, PSD, and low power underline a need for complex electronic designs that meet all of the requirements. Such readouts are not available from the commercial sector; therefore, they must be investigated through organized R&D efforts that involve all stakeholders.

5.4 ASSOCIATED PARTICLE IMAGING

The neutron source of an API system is made of an ultrahigh-vacuum chamber where accelerated deuterium ions are shot at a tritium-loaded target. By detecting the alpha particles emitted from fusion with a detector embedded in the neutron generator, better temporal and spatial cuts can be made, yielding better imaging performance.

A semiconductor alpha-particle detector is being developed at BNL in collaboration with ORNL and partnership with DT-generator vendors (i.e., Starfire). The detector uses a large (5×5 cm) monolithic silicon sensor that provides a spatial resolution of 0.5 mm for a total of 10,000 pixels (Figure 6). Silicon diodes can deliver good signals after a fluence of more than 10^{12} alphas/cm^2, which is the expected fluence at the end of the neutron generator's lifetime. Diamond sensors can be used instead of silicon if those values are to be exceeded.

The sensor electronics sit outside the generator chamber and consist of an ASIC capable of amplifying and low-pass filtering input signals for use by an FPGA that measures the time of arrival (TOA) and time over threshold (TOT) to provide a targeted time resolution of less than 1 ns.

5.5 STATE-OF-THE-ART ELECTRONICS

Neutron radiography detectors require a unique combination of desired characteristics:

- Low power
- High channel count
- Fast timing

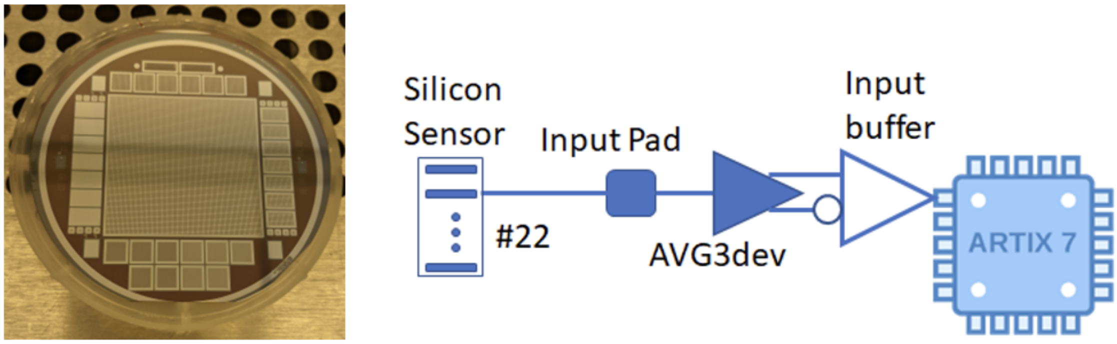


Figure 6. A new semiconductor alpha-particle detector. (left) Silicon wafer with a 5 × 5 cm pixelated detector and ancillary structures for testing purposes. (right) Block diagram of the system.

- PSD

No existing ASICs, developed at BNL nor elsewhere, meet all these requirements.

For example, the Liquid Argon ASIC (LArASIC), initially developed for the readout of the signal charge of liquid argon time projection chambers (TPCs) and later adapted for the readout of the light signal in photon-counting mode using SiPMs, is a purely analog programmable ASIC with outstanding noise performance and very low power (~6 mW/channel). In the readout of the nEXO experiment it is coupled to an external analog-to-digital converter and to a data multiplexer/driver, as shown in Figure 7.

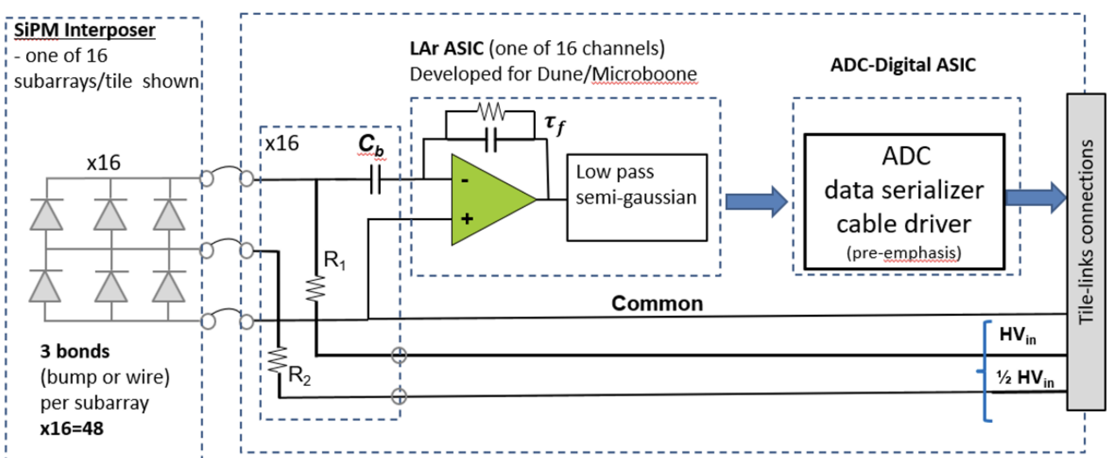


Figure 7. SiPM readout for the nEXO experiment.

Because each event is digitized, PSD can be obtained by digital signal processing in real time in the data acquisition system (likely an FPGA).

5.6 R&D RECOMMENDATIONS

The development of readout electronics generally follows two paths. The first path involves creating generalized systems that can process signals from a variety of sensors and measurement scenarios. These sensors are valuable for hardware development, but they usually sacrifice SWAP for this generality, making them poor choices for field use. The second path involves developing a system for a specific task or scenario. These systems can be designed to be low power without sacrificing signal processing throughput. However, this capability is usually limited to a few specific tasks. Applying these systems to other sensors or measurement scenarios can be challenging but can be an opportunity to save development time.

1. Applications that employ integrating detector panels and pulsed sources (portable high-energy x-ray sources are necessarily pulsed) that are in part limited by dark current in the detector (e.g., x-ray measurements of highly attenuating objects, neutron measurements for which the signal strength induced by present portable sources is low compared to dark current). Recommendation: develop and test readout of digital panels that enable separate accumulations of signal during the interrogating source pulse and dark current between pulses. Such panels will enable both reduction of dark current in the signal image and accurate determination of the dark current during the measurement.

2. Spectral and dual-energy pulse-counting x-ray detectors hold promise for drastically increasing the SNR for high-energy radiography by eliminating low-energy downscatter from images, enabling material identification using the relative intensity recorded in different energy bins, and attaining high resolution via event centroiding. Recommendation: evaluate the efficacy of pulse-mode x-ray imaging for high-energy radiography with pulsed sources using laboratory measurements that employ existing commercial spectral and dual-energy pulse-counting x-ray detectors. The present solutions require semiconductor converters, but the possibility of using a scintillator screen and photodiodes can also be evaluated for use with high energies.

3. Advanced readout is needed to enable efficient fast neutron imaging using the next generation of neutron imaging detectors and fast neutron sources. To achieve the desired efficiency, neutron detectors will likely employ organic scintillator volumes that are several centimeters thick and use fiber-optic light guiding or other optical segmentation to preserve position information. Recommendation: to enable best use of these detectors, develop scalable solid-state pulse-counting readout. The ideal embodiment of such readout would have the following capabilities:

   - Resolve depth of interaction from single-sided readout to preserve resolution when the neutrons are not normally incident on the panel (approaches may use timing or light sharing).
   - Resolve individual interactions from multiple scatters and identify the first interaction (requires approximately 100 ps FWHM timing).
   - Distinguish neutrons from gamma rays on an event-by-event basis.
   - To the extent possible, perform timing, localization, and PSD on chip at the detector.
   - Scale to areas of 1,000 cm^2.
   - Operate with low power. Power consumption of less than 100 W will enable a detector to run from a battery that can be transported on a commercial airline flight for a duration of more than 1 h. Power consumption of a few tens of watts may allow cooling without a fan for hermetic sealing.
   - Operate at rates up to $10^4/cm^2$ for neutron detectors and $10^6/cm^2$ for alpha detectors with minimal dead time.
   - Work as part of a system, for instance, to allow incorporation into an API imaging system.

   Approaches should involve conventional SPAD arrays (SiPMs) and digital SPAD arrays (PDCs) to enable single-photon counting capability. Approaches that presently use direct detection in semiconductor could also use indirect detection in the scintillator when combined with a black silicon photosensor that has photoconductive gain of approximately 100. This approach could be sensitive to approximately 10 photons. Approaches that employ SPADs will need to distribute scintillation light over a sufficient number of microcells to retain energy resolution.

6. RADIATION SOURCE DEVELOPMENT

Raymond Cao, The Ohio State University
Cameron Geddes, Lawrence Berkeley National Laboratory

6.1 INTRODUCTION

Active probing using penetrating radiation sources is essential for cases in which either the object of interest does not emit passive radiation or other signatures, or that passive emission is shielded or insufficiently specific. For cases in which passive signatures can be used, active probing offers more detailed information, including configuration and composition, that are important to applications [1, 27]. This section focuses on transportable systems and discusses how ongoing development may bring some of the advanced capabilities currently limited to larger facilities or vehicle-based sources to transportable applications.

The assets of active methods are balanced against size and operational constraints (e.g., shielding or operator distance requirements). As more advanced sources develop, the range and applicability of active methods—and the range of applications that can benefit from the resulting precision—are expanding. Furthermore, new sources have the potential to enable advanced signatures, which, to date, have been possible only in the laboratory for field applications. This section reviews the current state of the art of deployed sources and R&D of new sources and identifies R&D directions with potential to advance future applications.

6.2 X-RAY SOURCES

Commonly used active probing sources are x-rays, ranging from hundreds of keV to 10 MeV depending on the thickness of material to be penetrated. The 10 MeV upper range is determined by the desire to avoid photo-neutron production, which incurs additional regulatory and safety considerations. Currently deployed sources rely on simple production methods compatible with current accelerators at transportable scale. Advanced methods are emerging that could support greater precision with new accelerator technologies [20].

Many sources rely on bremsstrahlung to generate x-rays via interaction of a relativistic electron beam from a particle accelerator with a high-Z target such as tungsten or tantalum. In the target, interactions of the electrons with atomic nuclei decelerate the beam, resulting in broad-spectrum, forward-directed radiation. Owing to the very strong atomic fields, the x-ray endpoint energy extends up to the electron beam energy, thereby reducing demands on the accelerator. Consequently, such sources can have comparatively modest size, which has facilitated applications. The beam is forward directed, typically in cone angles of tens of degrees, and the beam intensity and pulse structure are controlled by the accelerator, allowing modulation. If neutron production is desired, then operation of the beam above 10 MeV can create a photo-nuclear neutron source. Radioactive isotope sources are well developed and are not the focus of current use or of this report because of limits, including potential for contamination and limited intensity and flexibility. They are always on and isotropic in emission, limiting flexibility and transportability, with several fixed-energy emission lines. Examples include ^{60}Co and ^{137}Cs.

More advanced sources are being developed based on Compton (or Thomson) scattering, in which photons from a counter-propagating laser are upshifted to MeV energies by being scattered from the relativistic electron beam from an accelerator [27, 20]. This process yields highly controllable x-rays with properties such as nearly mono-energetic distributions, low divergence ($<1°$), polarization, and picosecond to femtosecond pulses that can improve signal, reduce radiation dose and allow new signatures. Creating MeV x-rays requires hundreds of MeV electrons, which require substantial accelerator advances relative to bremsstrahlung sources to enable application scale systems. An alternative is nuclear reaction sources [27, 20] in which an ion beam on a target induces a beam-controlled nuclear reaction. Such sources are near isotropic in emission and typically have several nearly mono- energetic emission lines controlled by the target material. Some targets can also produce neutrons.

6.2.1 X-ray Signatures and Use

X-rays are most commonly used in radiography, which measures attenuation of material in transmission to form a transmission image of an object on a screen. Multiple energies can be used to infer the material's Z-number via the attenuation cross-section dependence on energy. For most sources, the endpoint of a broad distribution is adjusted, whereas mono-energetic sources could probe more precisely with discrete energies (Figure 8). The average energy of a 9 MeV bremsstrahlung source is in the 2–3 MeV range. At 3 MeV, attenuation is in the range of 10^{-5} in 40 cm of steel such that at least $\sim 10^8$ photons/resolution element are needed [20]. Often many more are needed because of scattering, detector efficiency and broad energy spread of the source. Similarly, broad angular spread can illuminate a whole target for quick scans using a large detector. Conversely, narrow emission angle can improve accuracy and reduce dose by limiting the contributions of scattering to the image. These traits could be further improved using pulsed sources and time gating. Sources with small emission spot sizes can improve spatial resolution.

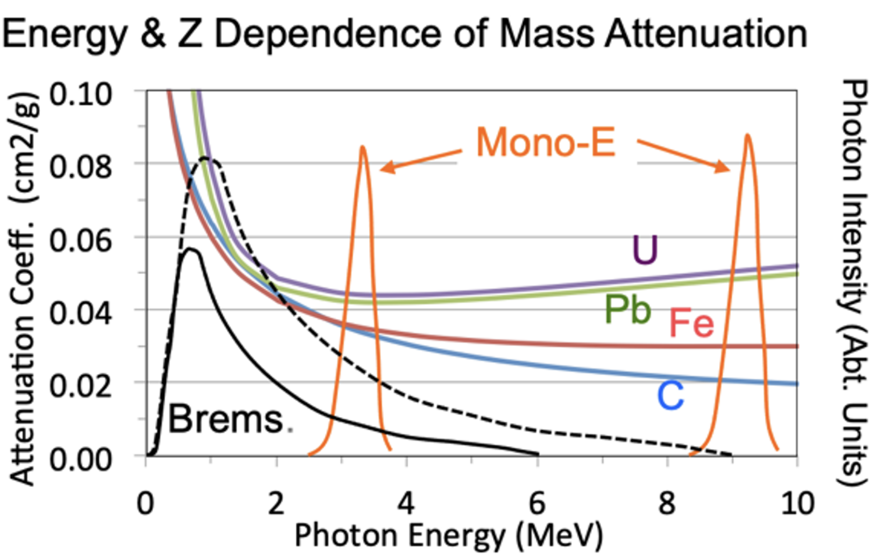


Figure 8. Attenuation cross-sections of various materials overplotted vs. energy. The energy spectra of bremsstrahlung and mono-energetic sources illustrate utility for transmission imaging and Z determination.

Signatures beyond radiography are not commonly in use in the field and have the potential to offer greater specificity to applications if they can be deployed [20]. Backscatter of a short pulse beam could uncover 3D information from a single-sided, single-view configuration that is operationally attractive. Photofission can be induced above 6 MeV with a peak near 15 MeV and a potentially attractive operation point at 9 MeV that limits photo-neutron contributions. Nuclear resonance fluorescence offers isotope-specific identification via a very narrow line, which prioritizes use of nearly mono-energetic sources.

6.2.2 Current State of the Art

Currently deployed x-ray sources are based on bremsstrahlung from relatively simple accelerators that support field deployment in both scale and robustness, including x-ray tubes and betatrons. At the same time, development of linacs (already used in fixed and vehicle-portable systems) promises improved performance in the near term for bremsstrahlung sources, while plasma-based accelerators offer a path to much smaller, positionable devices. Similarly, development of Compton systems based on linacs is offering high-performance signatures based on mono-energetic sources. Plasma-based accelerators offer a path to making such sources transportable. Table 4 summarizes sources, parameters, development status, and R&D needs.

X-ray tube–based sources are the most compact. They typically offer energies of 150–370 keV and yield of 2–5 mR per pulse in pulses tens of nanoseconds in duration at distances of 12 in. In such sources, which are compact and have not been scaled to high energies, a high voltage accelerates electrons. These sources can be handheld and weigh 6–18 lb, including a battery good for several thousand pulses. They measure in the range of 27–49 cm in the largest dimension. These characteristics, together with broad emission angles of 40° (with options for 60° and 84° and a panoramic option in development), facilitate rapid scanning. Because of the modest energy and dose, these sources are not used to penetrate thick targets. Examples include those from Golden engineering.

Betatron circular accelerators are deployed for multi-MeV transportable applications. The accelerator uses a magnetic induction mechanism to accelerate particles on a circular path into a target. Betatrons are compact enough to be person-portable in two packages. Typical scales are 140–450 lb: each part of the system is approximately 60–70 cm in the largest dimension and requires 1–3 kW level external power at energies of 2.5–7.5 MeV. Emission angle is typically 22°, and emission spot size is in the 0.3 × 3 mm range, varying by model. These systems are used to penetrate thicker objects. Suppliers include JME [45] and Instauro [44]. They produce moderate dose at the 0.7–5 R/min range—higher than tubes but lower than fixed linacs—and, owing to the circular beam path, residual radiation is emitted in all directions, possibly complicating shielding. Moreover, lack of a domestic supplier is a constraint.

Development is in progress on new bremsstrahlung sources motivated by the potential for greater tunability and control, increased stability, smaller photon emission spot size, reduced radiation footprint, and reduced size or access to higher energies at given size. organizations such as RadiaBeam [60], TibaRay [72], and SLAC [82] are developing several linacs at energies of 1–6 MeV as replacements for betatrons. Varex [28] has also done some development. Such accelerators are now in use in truck-based and fixed form factors. They use a metal cavity to shape the radio frequency (RF) field to accelerate particles. They offer smaller emission spot sizes at or below 1 mm and the potential for reduced shielding needs because the beam goes in a single direction. Systems under development target weights in the 200 lb range, lighter than betatrons. Dimensions are in the range of 0.3–0.6 m in the longest dimension for two-package systems (1.3 m for a single package), comparable to or smaller than betatrons. These systems are currently in technology development, and availability is anticipated in some cases as early as 2024. In the longer term, plasma-based accelerators using the radiation pressure of an intense laser to create a space charge wave in an ionized plasma support GeV per centimeter acceleration and hence potentially very compact systems. Technology development is working toward scaling of such systems to few-MeV energies, possibly enabling a few-pound, hand-positionable source head powered by a fiber from a laser with a path to weights below 200 lb and sizes comparable to or smaller than existing power supplies [35]. Such sources offer a path to positionable multiview radiography and advanced signatures such as a scanned narrow divergence beam for contrast, femtosecond pulses for backscatter, and sub-mm emission spot size for resolution. R&D is needed to support maturation, as described in the following subsection.

Motivations for development of new sources include increased specificity (10× in materials, 10×–1,000× spatial), reduced radiation dose (potentially 10×–100×) and/or increased penetration [20]. Control of spectrum, divergence, and pulse structure offer improved performance and new signature options. The Centurion ion linac by Starfire Industries [30] is one new source that is at a relatively high level of development. Its cart form factor can be loaded into a van. It produces few MeV protons or deuterons that interact with a target to produce a nuclear reaction with selectable mono-energetic MeV gamma lines determined by the target. Linear electron accelerator-based Compton scattering sources of mono-energetic, tunable MeV photons are being developed, including under the Defense Advanced Research Projects Agency (DARPA) Gamma Ray Inspection Technology (GRIT) program (e.g., by Lumitron [29] and RadiaBeam [60]). They target energies from 10 keV to 3 MeV at and above 10^{12} photons/s in a narrow divergence (<1° opening angle) beam. Energy spread down to less than 0.1% and photon emission spot sizes of 2–10 μ are targeted to enable highly precise signatures such as nuclear resonance fluorescence and will enable precision radiography and *Z*-number determination. Size goals are at the container scale and 13,000 kg. Development of plasma accelerators offers a path to scale mono-energetic sources to smaller sizes [35]. A proof-of-principle source (∼30 m^2 single-layer table in the lab) is operating at 1 MeV, 10^7 photons/shot, and energy spreads down to 20%. This source has been used for proof-of-principle high-resolution radiography (<0.2 mm now, with micrometer potential) and backscatter single-view 3D demonstrations. It is being developed to 9 MeV and percent-level energy spread. Additionally, compact lasers offer a path to transportable form factors and photon fluxes of $10^1 2$/s compatible with high-throughput scanning (e.g. 10 kHz for ∼$1m^2$/s through 40 cm of iron). The following subsection details the R&D needs of these technology developments.

6.2.3 X-ray Source R&D Recommendations

X-ray source development is based on the development of more advanced accelerator technology. Both near-term and long-term R&D are needed to realize improved sources for applications. Commercial suppliers of currently deployed sources conduct development internally and did not list needs for external development. Near-term shared needs for developmental sources such as linac-based bremsstrahlung systems include RF component development, prototype integration, and field and reliability testing. These efforts will be important to support transition of these relatively near-term technologies from laboratory to market and field use. Performance testing and validation are needed for near-term sources to guide deployment and also for longer-term candidates, such as plasma accelerator bremsstrahlung and Compton sources, to guide development and evaluate new concepts of operation enabled by emerging source properties. Longer-term shared development needs include advanced RF components and efficient lasers to drive linacs (nearer term) and plasma-based systems (longer term), respectively, in compact, robust packages. These efforts can and should leverage US Department of Energy (DOE) Office of Science efforts targeting elements needed for transportable systems. Guidance is needed from users in the performance–SWAP trade space to tailor development to address the most urgent needs. Development of modalities for new sources is also important, including, for example, taking advantage of pulsed sources and sources that could enable scanned fan beams, possibly by moving the source (proven to increase contrast in fixed applications). In particular, multimodal and scene fusion techniques discussed in other sections should be developed to incorporate active signature data.

Further development also requires support and partnering, including technology demonstrations and testing, incorporating user feedback. Application development should be conducted in partnership with detector and application specialists, leveraging novel properties that are emerging (e.g., pulsed, polarized, directional, mono-energetic). Partnering is also needed to support and evaluate integration and manufacturability/maintainability of new technologies and their calibration and configuration. Investment support for R&D across these lines is important.

Connections should be built with past programs and performers such as Varex linac efforts. Connections to ongoing programs such as the DARPA ACCEL (high-current accelerators), GRIT (mono-energetic sources based on linacs), and MuS2 (muon sources based on plasma accelerator) can leverage their development to advance imaging and related applications. Connections to DOE Office of Science programs that are developing the foundational technologies can leverage long-term R&D to realize new capabilities, for example from new particle accelerators developed for DOE's High Energy Physics program colliders or new lasers from DOE Office of Accelerator R&D and Production. The key needs per technology are listed in Tables 4 and 5.

More broadly, emerging accelerator technologies, from compact linear accelerators in the near term to plasma based accelerators in the longer term, are the key to unlocking improved x-ray sources. Tailored development to application needs is important, since scientific sponsors are not focused on transportability, or on MeV x-ray sources. At the same time, such development levergages large efforts in the development of these technologies for other applications. The development goals articulated in the Basic Research Needs on Compact Accelerators for Security and Medicine [18] should be supported.

6.3 NEUTRON SOURCES

For neutron imaging, various types of neutron sources are available, including isotopic neutron sources that use spontaneous fission sources (e.g., ^{252}Cf) and actinides blended with BeO powder to induce (alpha, Be) reactions (e.g., Am–Be or Pu–Be). Portable neutron sources, such as fusion tubes based on DD (2.45 MeV neutrons) or DT (14.1 MeV neutrons) reactions, are commonly used. Larger and more sophisticated neutron sources are also available, some of which are still arguably truck portable, such as linac photo fission, plasma neutron sources [74], and laser-driven plasma ion accelerator that enables tunable MeV directional neutron sources[20, 63, 50]. Large facility-based neutron sources include accelerator-based fast neutron production[61]; ^{7}Li (p,n), ^{7}Be, ^{9}Be (d,n), or ^{10}B reactions; spallation neutron sources; and neutron beams provided by research reactors[56]. A summary of neutron sources is given in Figure 9.

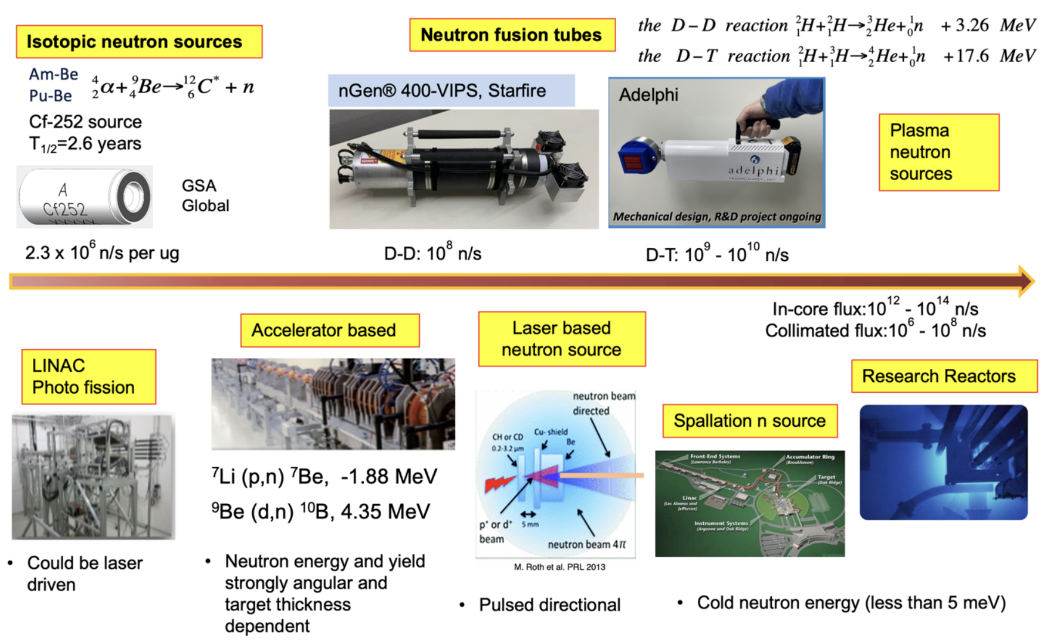


Figure 9. A summary of various neutron sources available for neutron imaging applications.

This subsection focuses primarily on portable fast neutron sources for neutron imaging. However, reactor-based neutron sources are also valuable assets because they provide a reference point for the quality of neutron imaging and can serve a metrology role. Typically, a neutron collimator or beam-shaping assembly is used to shape the neutron beam by blocking unwanted directions, often characterized by the ratio of the distance between the entrance aperture of the beam to the image plane to the diameter of the beam aperture (L/D ratio), which ranges from 50 to 1,000, depending on the beamline's length and the aperture size.

Table 4. X-ray source options, status, parameters, and development needs for deployed and linear accelerator development.

Technology:	Pulsed x-ray generators	Linear Accelerator	Linear Accelerator	Linear Accelerator	Betatron
Company/ institution:	Golden Engineering	Radiabeam Technologies, LLC	TibaRay Inc	SLAC National Accelerator Laboratory	JME, Instauro
Contact name:	Roger Golden	Surgey Kutsaev	Arun Ganguly	Brandon Weatherford	Website
Portability:	Hand and Man-Portable	Hand Portable	Man-Portable	Man Portable	Fixed
Technology status:	Shipping products since 1973	Technology Development, shipping in 2024	Technology Development	Technology Development	Shipping products
Emission spectrum:	Bremsstrahlung	Bremsstrahlung	Bremsstrahlung	Bremsstrahlung	Bremsstrahlung
Energy(s):	150 kV, 270 kV, 370 kV	0.2 - 2 MeV (adjustable)	1 - 2.5 MeV	2 - 6 MeV (adjustable)	2 - 9 MeV
Spot size:	3 mm	1 mm	<1 mm	1 mm	3 mm
Directional dose rate:	2–5 mR per pulse @ 30 cm	10 R/min	1 cGy/min to 50 Gy/s	0–10 R/min @ 1 m	0.7–5 R/min @ 1 m
Power requirements:	—	1 kw	1–3 kw (portable); 1.5 MW (fixed)	<400 W average power	1–3 kW
Weight:	2.6–8.3 kg	25 kg	200 lb	<250 lb	65,000–200,000 kg
Size:	$27 \times 10 \times 11$ cm^3; $49 \times 12 \times 18$ cm^3	$600 \times 400 \times 300$ cm^3	$12 \times 18 \times 9$ in.; $14 \times 14 \times 18$ in. (battery-powered modulator)	$2 \times 2 \times 4$ ft^3	$700 \times 430 \times 355$ mm^3; $607 \times 450 \times 570$ mm^3; control panel: $305 \times 275 \times 150$ mm^3
Near-term development needs:	—	Modular development, prototype fabrication, and testing	Resources for performance and reliability testing of prototypes	In prototyping stage. Need to validate x-ray beam characteristics with linac test and continue with prototype system integration for field demonstration	—
Long-term development needs:	—	New magnetron development, Ku-band RF components development, x-ray target development, field testing, reliability, wider band adjustable energy, better power sources	Resources	Better understanding of trade-off between SWAP, beam energy, spot size, and dose rate for different users	—
Partnering needs:	—	Investment in R&D, feedback from users, partnering with integrators for clean packaging	Partnering with end users for system testing and advice on commercialization requirements	Industrial/ government partnerships for system integration, tech transfer, and ruggedization. Discussions are on-going with government partners.	

Table 5. X-ray source options, status, parameters, and development needs for advanced systems development.

Technology:	LadiBug positionable mini-bremsstrahlung source	Laser Compton x-ray and gamma-ray source for nuclear assay and precision imaging	Mono-energetic photon source
Institution:	LBNL	Lumitron Technologies, Inc.	LBNL
Contact name:	Anthony Gonsalves	Chris Barty, Ferenc Raksi	Cameron Geddes
Technology status:	Technology Development	Accepting orders for R&D units	Technology Development
Emission spectrum:	Bremsstrahlung	Laser Compton, mono-energetic, quasi-collimated, angle correlated spectrum	laser compotion, quasi mono-energetic (current) 20 - 50% DE/E (potential) < 1%
Energies:	(potential) 0.5 - 10 MeV	30 keV - 3 MeV	(current) 0.1 - 2 MeV / (potential) 0.1 - >10 MeV
Spot size:	(potential) 0.1 mm	2 - 10 μm	(estimated) 0.1 - 5 μm
Power requirement:	(potential) 3 - 6 kW	300 kW	(current) lab system 10's kW at low rate (potential) kw to 10's kWe or higher depending on rate
Weight:	(potential) <200 lbs	13000 kg	(current) lab scale (near term) moving van scale (potential) smaller systems
Size:	(potential) emission head $0.2\times0.1\times0.1$ m^3; laser supply $0.5\times0.5\times1$-1.5 m^3	$12\times2.35\times2.39$ m^3	(current) lab scale (near term) moving van scale (potential) smaller systems
Near-term development needs:		Understanding customer infrastructure and needs for e-beam dump configuration	
Long-term development needs:	Flexible fibers for laser delivery, small source head with gas management, compact and efficient laser technology	Partnering with technology demonstrations	Extended energy range to 9 MeV, flux to 10^8/shot, energy spread to 1%. Efficient, high repetition rate laser technology
Partnering needs:	Signature and detector testing, application evaluation	isotopic and element specific materials detection, assay and imaging	signature and detector development to leverage novel source, new signature development and application evaluation

Collimation is an inefficient process to achieve a parallel beam because it obtains approximately one neutron out of 100,000–1,000,000 in-core neutrons (as a rule of thumb). Despite this limitation, research reactors offer high-resolution neutron radiography and tomography capabilities. API provides a "collimator-free" alternative for neutron generators to achieve collimation. The current technology relies on expensive YAP:Ce detectors that are not manufactured in the United States. Additionally, the 256 × 256 pixel configuration presents a challenge for readout time because the numerous pixels could cause jams. Therefore, a time resolution of 500 ps is desired for optimal results.

The number of neutrons, as well as SNR, significantly affects resolution and imaging time. For an intuitive comparison of the scale, note that a high neutron flux of 10^7 n cm^{-2} s^{-1} will only have 0.1 n μm^{-2} s^{-1}; that is, only one neutron is received per square micrometer every 10 s. Therefore, higher neutron flux is always desirable to achieve better spatial resolution in a reasonable amount of time. Although resolution at the millimeter scale is mostly practical with portal neutron sources, achieving resolution at the micrometer scale will induce long imaging time, and the nanometer scale is currently impossible.

The neutron yield for neutron generators depends on many factors, and many trade-offs must be considered. These factors include acceleration voltage, high-voltage breakdown, beam current, spot size, target thermal conductivity, metal consumption by sputtering, cooling, and dehydrogenation temperature. Moderation vs. collimation vs. API for "collimation" must also be considered. API prefers small spot size, which limits neutron yield. A high-flux neutron generator will have a larger spot size. Because most of the neutrons are emitted along the forward direction, the moderation pack must be designed accordingly to achieve desired thermal neutron flux. The lifetime of the generator heavily depends on the customer or user, as does tritium management if tritium is used. Additionally, helium gas buildup might cause concerns, and SWAP must be considered. Table 6 presents an example commercial off-the-shelf neutron source.

Customers must consider several important factors when choosing a suitable neutron source for field neutron-imaging applications. For example, small spot areas, such as those with a diameter of approximately 2 mm, offer better spatial resolution owing to cone beam geometry, but they also have lower neutron yields. Conversely, larger spot sizes provide better neutron yield and are better for heat removal: small spots may become overheated, resulting in the release of deuterium or tritium. In terms of the ion source for a neutron generator, DD gas mixture and DT gas mixture are commonly used. The target can be made of metal hydride, with thin films of titanium, scandium, or zirconium deposited on silver, copper, or molybdenum substrates. A thick target is used to compensate for the materials lost because of sputtering, whereas a thin target can have advantages for cooling. Alternatively, a beam-loading target is often considered to maintain neutron yield of DT systems and thus extends the useful lifetime of the generator. For absolute maximum neutron yield (per milliamp) many engineering trade-offs must be considered.

When it comes to standards for quantifying the quality of neutron sources and imaging procedures, the American Society for Engineering Education has published several standards for reactor-based neutron sources. For example, E803-91 is a standard method for determining L/D ratio, E748-02 provides standard practices for thermal neutron radiography, and E545-99 is a standard test method for image quality in radiographic examinations. Similar practices may be developed to establish fast neutron imaging standards.

The development of accelerator-based neutron sources has witnessed significant advancements, primarily owing to the renewed interest in boron neutron capture therapy [12]. The $^{7}Li(p,n)^{7}Be$ reaction exhibits a significantly higher neutron yield (e.g., 9.3×10^{11} n/mA) at lower proton energies (e.g., at 2.5 MeV) compared with the $^{9}Be(p,n)^{9}B$ reaction (e.g., 3.9×10^{10} n/mA) [7, 22]. Generally, a lower energy requirement for particle-induced neutron production translates to a more compact and cost-effective accelerator, which in turn demands less space for its installation. Deuteron emerges as a favorable candidate for neutron production because it is involved in several reactions (e.g., d–Li, d–Be, and d–^{13}C), with substantial neutron yields (10^{11} n/mA) even at low bombarding energies (≥1.5 MeV). However, a 30 MeV cyclotron system occupies a

Table 6. Portable neutron sources summary

Model	Maximum neutron yield	Typical tube lifetime	Operating mode
Thermo Fisher Scientific, Inc.			
API 120	2.00×10^{7} n/s	1,200 h @ 10^{7} n/s	Continuous only
D 711	$2.00 \times 10^{1}0$ n/s	1,000 h @ $10^{1}0$ n/s	Continuous only
MP 320	1.00×10^{8} n/s	1,200 h @ 10^{8} n/s	Continuous and pulsed
P 2011	1.00×10^{8} n/s	up to 400 h or greater	Continuous and pulsed
P 385	5.00×10^{8} n/s	4,500 h @ 10^{8} n/s	Continuous and pulsed
GENIE 16	2.00×10^{8} n/s	8,000 h @ 5×10^{7} n/s	Continuous and pulsed
GENIE 35	$10^{10}/4\pi$ n/s/sr	2,000 h @ $10^{10}/4\pi$ n/s/sr	Continuous and pulsed
Adelphi Technology, Inc.			
DD108	1.00×10^{8} n/s	>2,000 h	Continuous and pulsed
DD109.1	1.00×10^{9} n/s	>2,000 h	Continuous and pulsed
DD109.4	4.00×10^{9} n/s	>2,000 h	Continuous and pulsed
DD109 M	4.00×10^{9} n/s	>2,000 h	Continuous and pulsed
DD110 M	1.00×10^{10} n/s	>2,000 h	Continuous and pulsed
Starfire Industries			
nGen 400	5.00×10^{9} n/s	>2,000 h	Continuous
All-Russia Institute of Automatics - VNIIA			
ING-013	5.00×10^{9} n/s	1,600 h @ 10^{8} n/s	Pulsed
ING-03	3.00×10^{9} n/s	1,600 h @ 10^{8} n/s	Pulsed
ING-031	2.00×10^{10} n/s	1,600 h @ 10^{8} n/s	Pulsed
ING-07	1.00×10^{9} n/s	—	Continuous and Pulsed
ING-17	3.00×10^{8} n/s	—	Continuous and Pulsed
ING-27	1.00×10^{8} n/s	—	Continuous
ING-14	2.00×10^{10} n/s	—	Continuous
ING-10	5.00×10^{8} n/s	—	Pulsed
ING-12	2.00×10^{9} n/s	—	Pulsed

space of 110 m^2 [70] and is deemed an immobile source. Although the feasibility of portable or transportable neutron imaging systems equipped with an accelerator-based neutron source presents challenges, it remains a worthy endeavor to explore, given the rapid advancement within the field. Additionally, these sources hold the advantage of being classified as medical devices, resulting in a lower regulatory threshold for both users and providers compared with nuclear reactor sources.

When deuterium gas is used, plasma-focus devices produce bursts of neutrons that endure for roughly 100 ns, exhibiting energies spanning from approximately 2.1 to 3.1 MeV [68]. These devices are promising as a viable option for fieldable neutron imaging if their size can be reduced to meet the SWAP requirement.

6.3.1 Neutron Source R&D Recommendations

For future R&D, the following are recommended:

1. Develop high-yield neutron sources for field neutron radiography demonstrations, with the consideration for dimension scale down.
2. Develop compact neutron sources for field neutron radiography applications.
3. Develop alternative pixelated alpha detectors with a wide-bang semiconductor as a replacement for the scintillator-based detector to improve the transit time. The readout circuit for the 256 $\times$ 256 pixel array must also be fast.
4. Standardize the fast neutron imaging testing target, testing procedures, and quality indicators.

7. ALGORITHM DEVELOPMENT AND DATA FUSION

Erin Miller, Pacific Northwest National Laboratory
Brian Quiter, Lawrence Berkeley National Laboratory

7.1 CURRENT STATE OF THE ART

Algorithms, data fusion, and visualization collectively (hereafter referred to as simply "algorithms") are used to take measurement data and process, display, or interpret them in a way that supports decision making. Algorithms for field radiography include functionality not only to measure the target's dimensions but also to support feature detection and identification by the operator. Several potential algorithm/data fusion/visualization approaches that may be relevant for field radiography are already used in other applications or in laboratory settings or are currently being developed. Adjacent fields, including medical imaging, nondestructive evaluation, and security screening represent a significant pool of expertise and development. Additionally, as new tools or measurement techniques are incorporated into field radiography, algorithm technology must advance as well. This section discusses the state of the art for field radiography algorithms and describes other radiography algorithm technologies that either are applied in laboratory settings or are more advanced in their development for other fields. Based on this summary, and discussion from the radiation imaging community, this section presents recommendations for future R&D.

7.1.1 Existing Algorithms for Field Radiography

At present, radiography algorithms are typically used in field applications not only to measure the target's dimensions but also to support feature detection and identification by the operator. The following capabilities are typical:

- Display contrast adjustment
- Contrast enhancement, via noise reduction, edge sharpening, and/or down-binning
- Image stitching
- Dimensional measurements either supported by manual measurements of setup geometry or through incorporation of fiducials
- Creation of approximate 3D models based on combining two orthogonal views (supported by manual measurements of geometry)

Many such capabilities are integrated into the XTK software [36], which is a good representative of the state-of-the-art in field radiography algorithm capabilities. XTK also supports radiographic data acquisition with dose and exposure estimates as well as organizing mosaic images into a larger composite image.

7.1.2 Existing Algorithms from Other Fields

Advances in algorithms created by other fields or for laboratory-based use can be leveraged to enable more rapid improvement in field radiography. Adjacent fields with technologies that may be relevant include airport and cargo screening, which use emplaced radiography equipment but a wide variety of objects, and diagnostic and therapeutic medicine, which use high-fidelity systems on biological material. This subsection discusses current work that may be of value to field radiography. The WORIA workshop was organized around a number of areas for desired improvements in field radiography capabilities; to best identify algorithm work that may be relevant, this discussion follows the same structure.

Extensive R&D in clinical imaging and image fusion for reliable and consistent imaging with minimal tuning parameters represents a large resource of expertise to be leveraged [24, 42, 78]. The field of image fusion is too extensive to comprehensively list here, but two potentially relevant example methods of image fusion in clinical settings are multiscale decomposition methods and colorized alpha blending. The multiscale method follows a "decompose–fuse–reconstruct" workflow, and the transforms typically split the data into high- and low-frequency data (e.g., Laplacian transform, discrete wavelet transform). The colorized alpha blending method overlays information from a one modality with a second modality using false color maps and is commonly used to display positron emission tomography images over x-ray computed tomography images.

Improved Signal-to-Noise Ratio

Two main approaches are typically used to algorithmically improve image SNR. One leverages physics to remove effects of radiation scatter. This approach is often closely coupled with the physical radiographic system (e.g., timing and energy signatures) [69, 41] but can also take ancillary information into account. Once signatures associated with scatter are well defined, algorithms may remove them. Potentially, areas without complicating features (e.g., object edges) can be used to fit scatter effects, which may then be applied throughout the image [59]. However, scatter removal induces more complicated uncertainty analysis.

The second approach to improving SNRs involves using data-driven approaches to remove noise and/or enhance signal. Models of noise distributions can be formulated and applied to filter out image noise, and templates of expected "signals" may be formulated to selectively highlight them in lower-SNR images. Again, applying noise models and enhancing signal complicate uncertainties, which therefore need to be discussed. machine learning (ML)-based approaches may also be used to extract signal templates.

Finally, combining multiple images and/or multiple physical radiography modalities has the potential to improve overall SNR. This approach is discussed further in the following subsections.

MeV Photon Beams

Algorithms to exploit the phenomena produced via radiography with photon beams in the MeV energy range have been the subject of substantial R&D. Many such algorithms have been implemented at accelerator facilities throughout the world. Often the algorithms are tightly coupled to the radiation-detection hardware and the specific parameters of the source (e.g., collimation and pulse profile). One example of such algorithms is the use of temporal gating, which can improve SNR either by reducing sensitivity to ambient radiation or by enabling photon scatter rejection, which would require nanosecond-scale detector timing resolution and comparable or shorter beam pulses in order to differentiate direct radiation from scattered photons, which have traveled a longer distance to reach the detector.

MeV photon beams may be formed via bremsstrahlung or may comprise a more narrow energy spread from other production processes. Regardless, algorithms that are designed to exploit variable beam energies have been implemented foremost for cargo scanning applications [49, 37, 62]. Exploiting such capabilities in field radiography would be a natural extension if such equipment were fielded and easily co-aligned.

Beyond beam-coupled algorithm development, detector-coupled development is also ongoing [84]. MeV beams result in detector signatures that can have centimeter-scale (or more) spatial extents owing simply to the photon interaction physics within the detector system. Accurately recovering the location of radiation incidence would improve the spatial resolution of MeV beams. Similarly, spectroscopic and gamma-ray imaging techniques such as Compton and coded mask imaging could improve detector performance.

Material Identification

A broad range of activities are underway to improve the ability of penetrating imaging to provide some level of material information, in addition to geometry. X-ray attenuation depends on material thickness, density, and Z-number in combination. Some work is underway to estimate, or at least constrain, materials based on a single x-ray radiograph and assumptions about material properties and object geometry based on prior knowledge. At lower x-ray energies, dual-energy imaging, along with an estimate of path length, can provide enough information to separate estimates of material density and effective Z-number because of the trade-off between photoelectric absorption and Compton scattering. The path length estimate may be based on 3D information from multiview or CT data or based on prior knowledge or assumption about geometry. This approach can be generalized to the use of multiple energies or spectra to obtain a more refined estimate, especially for higher-Z materials, possibly improved by using regularization. New developments in spectral imaging detectors can enable this approach, although they are still limited in size.

The addition of neutron radiography can also enhance the acquisition of material information. Neutron cross sections are distinct from photon cross sections, providing complimentary information that can be leveraged to improve material discrimination, shown in the literature by methods such as 2D histogram segmentation [32, 31]. Neutron interrogation may also produce particles via reactions. These particles can be detected directly, although count rates are low and background rates are high. However, with the use of API, transmitted neutrons can be distinguished from elastic or inelastic scatter events, and induced reactions can be mapped as well, resulting in the ability to distinguish materials such as hydrogen or fissile materials.

Additional material information may be obtained from coherent scatter of x-rays or neutrons. For fast neutrons, small-angle coherent scatter can be measured during an API experiment and carries information on the size of the nucleus and is proportional to atomic number. For photons, small-angle coherent scatter can be detected during a phase contrast imaging radiograph along with a differential phase image and an absorption image (conventional radiograph). Because the differential phase is proportional to electron density gradients, phase can give density and effective Z-number information if the phase signal is integrated, whereas the dark field image can be processed to detect sub-resolution microstructure in the material. These techniques are being explored for security applications. At larger scattering angles, coherent scatter information can provide molecular structure information owing to x-ray diffraction. Although this technique is difficult to scale to penetrating energies, it is being developed for explosives detection in aviation security settings.

Some algorithms developed for material discrimination are highly tailored to enable the specific measurement approach in question. However, commonalities exist in algorithm needs for material discrimination. First, these methods are quantitative, so having a full understanding of the radiation transport processes, including in particular Compton scatter and beam hardening, can be essential to reliable interpretation. In many cases, quantitative techniques benefit from the use of reference data to detect small changes, a challenge for field applications. Algorithms can help address these issues, based on detailed modeling of physics processes, combining multiple measurements for enhanced understanding, or empirically fitting data to aid in extracting quantities of interest. In many cases, cross sections have limited specificity and the SNR may be low, so constraining the inverse problem is important. Furthermore, as algorithms grow more sophisticated and are integrated into the measurement and interpretation process, an understanding of how algorithm choices affect the uncertainty of the result is critical. The visualization and data fusion aspects are important in this area as well. For multi-energy x-ray, color overlays are a common way to display and combine information: different energy measurements can be displayed in different colors. Similar approaches may be of value for other combinations of material signatures.

Single-Sided Imaging

Single-sided imaging offers an important capability for field radiography when full access to an item of interest may not be possible. Several approaches can be used for single-sided imaging. The most mature approach is x-ray backscatter imaging, in which an x-ray source is used to illuminate an object and the Compton scattered radiation is measured in the backward direction. This technique has been deployed commercially using a raster-scanned pencil beam and a nonimaging detector. It has also been used as a fan-collimated source with translation and a collimated linear array. Other approaches under investigation include the use of a coded aperture array and imaging detector with cone-beam x-ray illumination, the use of a pulsed MeV-scale pencil beam with a time-gated detector for depth resolution or material information, and the detection of induced reactions.

As with material discrimination, many of the algorithm approaches for single-sided imaging are specific to the measurement technique at hand. Coded aperture imaging, for example, includes the use of specific deconvolution approaches depending on mask design, whereas the use of a pulsed beam and timing information requires careful integration of equipment and high-speed processing. For any backscatter approach, attenuation of the incident and emitted radiation will affect the signal. For quantitative analysis, this attenuation may need to be modeled, and attempts to leverage multiple beam energies to infer this information are underway. Regardless, qualitative imaging may still have value. Many of these techniques will have SNR considerations as well.

3D Imaging

Producing a 3D representation of the contents of an object could greatly aid decision-making in field radiography. Many techniques that exist in a laboratory setting can build toward this information: transmission computed tomography, in which projection images all around an object are reconstructed into a voxel-by-voxel map of attenuation; emission tomography, in which emission images are similarly reconstructed to produce a voxel-by-voxel map of emissions (albeit modified by attenuation); and induced-reaction or time-of-flight imaging, in which interaction location can be inferred by a combination of timing and collimation. Most of these techniques require some form of processing to interpret the data as a 3D image; the form of that processing is technique dependent. This discussion focuses on image formation via CT algorithms, which can be applied to both transmission and emission imaging and are supported by a large and varied field of development in medical imaging and nondestructive evaluation. For other techniques, algorithms for image formation are stronly technique dependent. Considerations about visualization, feature extraction, and uncertainty quantification can be expected to apply to any 3D imaging technique.

Tomographic techniques are quantitative, require good knowledge of data acquisition geometry, and are heavily algorithm dependent. All tomographic approaches require an excellent knowledge of equipment placement during a measurement. The most basic type of reconstruction assumes regular angular sampling, with the number of angles sampled proportional to the number of pixels—transmission CT in a laboratory setting can involve thousands of angles at well-spaced intervals. At the other extreme, some solutions for combining two views into an approximate 3D visualization are available for field use. This functionality is highly desirable but, in practice, takes careful alignment of components, and the information collected may not fully support a full voxel-by-voxel estimate of material properties. Other few-view methods are based on testing assumptions or models of the object and determining agreement with measurements. An extreme version of few-view tomography is freehand tomography, in which position and orientation information is collected in real time and equipment is moved freely. In other fields, a vast array of approaches attempt to reduce the number of angles measured while maintaining 3D image quality. The specifics of the approach tend to vary with the object being imaged. Generally, fewer angles support a less detailed or less accurate representation of the 3D object. Furthermore, the spatial resolution of the reconstructed objects sets the scale for the positioning accuracy required: a high-resolution reconstruction requires precise knowledge of source and detector position and orientation, and a lower resolution reconstruction has less stringent constraints. In either case, controlling or measuring this information in the field may pose a challenge to general applications.

Analytic reconstruction techniques can be relatively fast computationally but require regularly sampled measurements. Iterative or algebraic reconstruction techniques are more general and can support a broader range of acquisition strategies, models, or regularization parameters, but they are much more computationally intensive. Many of tools are available for CT reconstruction, including publicly available software [34] or packages developed for DOE-related work. ML is increasingly being incorporated into 3D imaging. For tomography, ML can be used to improve an otherwise noisy or undersampled reconstruction—with the caveat that ML implicitly incorporates a modeled understanding of data.

Visualization of 3D data is a more significant challenge than for 2D data. Data can be viewed as a collection of 2D slices, or, with the choice of a threshold value, a 3-D rendering of a surface can be produced and manipulated. If 3D data are provided to operators, then adequate visualization tools must also be provided. Standards for visualization from other fields such as aviation security may provide a useful example. Other useful functionality could include highlighting regions of interest. This highlighting could be performed in a variety of ways, including ML. Finally, quantifying and conveying uncertainty to operators remains important. Undersampled data, beam-hardening effects, scatter, and position or orientation uncertainty can all cause systematic artifacts in reconstructed data and can be difficult to quantify. Incorporating regularization terms or a model (whether physical or data-driven) can also result in uncertainties that are difficult to define.

Gains in Practicality

Radiation imaging algorithms are being leveraged to provide practical solutions to many of the logistical challenges that are faced in field radiography [25]. Two main thrusts of such algorithm development are automating analyses and coregistration.

Rather than improving image quality, ML and/or other classes of algorithms can be used to perform feature recognition or simply to automatically highlight features to the operator. This type of research is subject to significant evolution as generative artificial intelligence models become more widely available, but the need for representative data will remain a challenge.

Because tomographic imaging is often impractical in field applications, researchers are developing approaches to automatically analyze radiographs and measurement geometries to suggest subsequent measurement configurations that are predicted to provide the best reduction in image uncertainty.

Achieving material identification and 3D models in the field are two aims that can directly benefit from algorithmic approaches that fuse multiple measurements and/or the equipment of multiple scanning systems. However, algorithms that perform such automated data fusion require co-registration of the independent data stream. Tools that facilitate such co-alignment, co-registration of multiple measurements, multiple scanning systems, and/or obviate reliance on fiducials are also becoming available for field radiography. Commercial equipment from Faro [17] and Creaform [8] can produce sub-millimeter-resolution 3D models over limited areas, but they are not readily customized to provide information that would be useful to data fusion algorithms. Meanwhile, the hardware and analysis frameworks that were initially developed for robotics research are open source and readily customized. The work performing multimodal radiological data fusion [75] and a specific implementation for digitizing nuclear diagnostics scenes [65] could be further customized to meet field-radiography requirements.

Various radiographic methods and fusion approaches require significantly different levels of precision. High-energy radiographs that are limited by detector spatial resolution will never benefit from sub-millimeter resolution, whereas other methods would. Likewise, creating digital models and renderings that can be interacted with remotely (i.e., the concepts of virtual reality and augmented reality) has practical benefits. Although these technologies are becoming commercially available, their integration into field radiography has yet to begin. However, one could imagine an off-site expert viewing a field-measurement operation through virtual reality and giving real-time feedback to operators via augmented reality.

Cross-Cutting Pieces An important cross-cutting aspect to field-radiography algorithm development is the need to develop methods of quantifying the uncertainty associated with the coupled measurement and algorithmic assessment. This need becomes more important and challenging to address when algorithms become more complex and when multiple modalities of information are combined. Likewise, for inversion problems in the presence of statistical uncertainty and correlated and nonuniform sensitivity (in the imaging sense), regularization and incorporation of priors may occur, resulting in more complicated uncertainty estimates. The situation is more challenging because it can be difficult or impossible to produce relevant uncertainty estimates without the incorporation of prior knowledge or assumptions in the uncertainty estimation process. Developing user-friendly methods of incorporating priors is typically a laborious process, and solutions tend to be problem specific.

Forward modeling is a common method used in algorithm development. Ensuring that physical data fed to models are accurate and sufficiently available for training also applies to such algorithm development activities. Likewise, data-driven models require quality data—and often large quantities thereof—which may be practically difficult to obtain or generate.

Visualization of algorithm outputs and the uncertainties associated with algorithms is another cross-cutting aspect of field-radiography algorithms. Humans tend to disregard unexpected findings (confirmation bias) unless they are able to convince themselves that the algorithm is performing correctly. This assurance is often achieved via visualization. Therefore, as algorithms become more complicated, they must provide easy-to-digest visual evidence of their accuracy and efficacy. In scientific applications of ML environments, the field considers explainability a key aspect of any ML-based discovery.

Finally, most algorithmic topics discussed in this section highlight data fusion as a method of improving overall field radiographic system efficacy. Combining multiple radiographic images, radiographic data collected by different systems or the same system under different configurations, and combining radiographic data with passive detection data and/or visual information are all subjects of ongoing, potentially influential, study.

7.2 R&D RECOMMENDATIONS

7.2.1 Considerations for R&D Investment

Several aspects of R&D investment in algorithms for field radiography should be considered. Many of the following points are motivated in part by discussions that took place during the WORIA workshop. A great deal of variation can also occur in the time frame over which an area of investment may be influential. Incremental improvements in algorithms already in use, such as for image stitching or display or for contrast enhancement, may be readily adapted for field use. By contrast, some advances related to new hardware or techniques may require a much longer development time but may offer greater than incremental improvement.

One significant concern for potential R&D investments for field radiography is their operational compatibility. In addition to providing important information about an object being radiographed, field-radiography techniques must be extremely physically robust to be deployed in diverse environments. Approaches must also be robust in their implementation—reliance on very careful alignment, or multiple complex subsystems, may indicate that a technique is more challenging to transition to field use. Robustness is also a consideration for data fusion approaches, which require multiple types of information and often detailed physical setup. Computationally, a role exists for algorithms that are lightweight and can quickly provide results using laptop-like resources. However, more computationally intensive or slower methods, which pass information an off-site computational facility or to off-site experts for processing, are also relevant. In this scenario, the amount or speed of information that can be transferred in either direction may be severely limited; this capability also may not be available in all cases. Algorithms used in the field must be straightforward to operate and interpret. Users should not need to fine-tune algorithm parameters in the field, and results must be displayed in a straightforward manner to support decision-making. Ideally, uncertainty in results should also be quantified and conveyed to the operator. Finally, timing can be important for field radiography. Information, even if it is partial, should be displayed as soon as possible. Simple processing that can be completed quickly has value even in the presence of more powerful techniques that require more time to achieve results.

Some algorithms are uniquely tied to the technique they are developed for or are driven by new equipment or techniques. In many of these cases, algorithm development may not be readily decoupled from hardware development, and close collaboration is required. Examples may include image formation from neutron API or from pulsed photon beams. However, when the algorithm is not intimately tied to the acquisition mode, independent development may have value. Topics such as noise removal, contrast enhancement, CT algorithms, feature identification, uncertainty quantification, and visualization techniques can leverage extensive outside expertise in a manner that is less tied to hardware development. Enabling independent algorithm development, particularly by researchers working in areas outside field radiography, requires infrastructure to aid development in the form of needs communication, datasets for training and testing, and standards or methods to evaluate performance. Additionally, even those algorithms that are tightly coupled to the associated hardware could benefit from development using external perspectives. Therefore, an ethos of sharing data, metatdata, and documentation and of collaboration should be embraced by many field-radiography R&D projects.

7.2.2 Recommendations for R&D Investment

Data Fusion

Data fusion involves combining different measurement modalities to improve decision-making. Data fusion can take place at a low level, where shared physics informs interpretation, or at a high level, where multiple detection metrics are combined. Many of the techniques under consideration for enhanced spatial or material information can be conceived of as a type of physics-informed data fusion, including CT, combining radiography with passive radiation measurements, multi-energy x-rays, x-ray and neutron combined measurements, and phase contrast. Higher-level data fusion can include incorporating optical imagery or positioning information. Data fusion will often require some level of information about equipment positioning in order to register images. Fused data can be more complex to inspect and may benefit from improved visualization tools. Finally, understanding how uncertainty is propagated through the data fusion process is crucial. Specific recommendations are as follows:

- Fuse low- and/or high-energy x-ray and neutron radiography systems to improve material identification.
- Create the 3D, ultra-few-view approaches, and visualization techniques that are needed for field applications.
- Automate scene generation to eases the burden on operators while providing highly accurate measurements for simulations.
- Fuse radiography and passive measurements.

Machine Learning, Model-Informed Algorithms, and Visualization

Collecting sufficient information within the constraints of a field measurement, where time and equipment are fundamentally limited, is a challenging proposition. One cross-cutting area which can help is making the most use possible of information already known. This can include knowledge of the setup geometry, understanding of radiation transport properties, constraints that might be present on the object of interest, or prior experience from other measurements. Incorporating prior information in the form of a physics-informed model or a data-informed model can be a powerful tool for improving understanding. Prior information can also be invaluable for tasks such as automated feature recognition. However, it is difficult to quantify the uncertainty in a conclusion when a model is used. Care must be taken to ensure that while model use should inform results, it should not determine them. Finally, the ability to visualize algorithm output along with raw complex data streams are needed to assist users in understanding what is being measured but also to provide greater confidence in the measurement. Specific recommendations are as follows:

- Pursue object recognition/classification at low energies to automatically detect objects in the image.
- Investigate model-informed methods to connect with fast forward models.
- Improve error propagation for models.
- Improve visualization methods for displaying uncertainties in radiography data streams, displaying complex data/algorithm output, and overlaying or combining output from sources such as x-ray, neutron, and/or optical.
- 3D renderings of a scene are needed.

Support for Outside Development

Expertise is considerable in areas adjacent to field radiography. This expertise may be leveraged to improve the state of the art. Furthermore, advances in ML techniques depend heavily on the availability of large datasets. Support is needed to identify existing data and descriptive metadata that could be provided to developers. Information about performance requirements, particularly in the form of standards for evaluation, is also needed in order to enable development. Algorithms that are more closely coupled with measurement technique development may require closer collaboration, but collection and annotation of datasets and development of standards may still be of value to the community. Specific recommendations are as follows:

- Review the available data (and how available they are).
- Consider what additional data are needed by the community.
- Define standards and methods for algorithm performance evaluation.

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