Small Controlled Area Radiography – Fundamentals and Technology Advancements

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Abstract

Radiographic testing (RT) is one of the most efficient and economic NDT methods for volumetric inspection; ensuring safe, reliable construction and ongoing use of critical infrastructure around the world. The penetrating radiation from isotope based gamma ray and accelerator based x-ray generators provide a unique mechanism for creating an image based on the differential absorption of photons in a sample. Unfortunately, the mechanisms of photon radiation interactions with matter that allow for weld quality inspection, measurement of corrosion/erosion in pipe wall, etc. create negative externalities in many environments where RT is often performed.

- Gamma radiation interferes with critical safety and process control systems. Examples include UV flame detectors, radiation monitoring systems, nuclear level and density gauges, etc. These systems cannot differentiate the gamma rays from a radiography source and the UV photons from a fire or gamma rays from $^{137}\text{Cs}$ sources used in many nuclear gauges.
- ALARA – The ever-increasing emphasis on reducing occupational exposure and exposure to members of the general public often requires RT to be performed in shooting windows or during off-shifts reducing overall inspection efficiency.

SCAR or Small Controlled Area Radiography is the concept of controlling the radiation utilized for RT allowing for radiographic inspection without restrictive shooting windows (24/7 radiography concept), in close proximity to other trades, and without impacting critical sensor systems. This paper describes the fundamental principles for achieving Small Controlled Area Radiography with an emphasis on the use of $^{75}\text{Se}$ and innovations in SCAR equipment enabling advanced SCAR techniques. Practical SCAR applications covered include:

- Near nuclear gauges and UV detectors – typically <0.5 mR/hr
- Close proximity to members of the general public – <2 mR/hr exclusion zone at 6 feet
- Minimizing/eliminating flash dose
- Rope access

Keywords: radiography, SCAR, VFD, exclusion zone, $^{75}\text{Se}$

1 Problem Definition

1.1 Critical safety systems – UV flame detectors

Optical flame detection systems are a key component of critical fire safety systems in industrial environments where highly combustible materials are present, instantaneous response to flames is needed, or automated fire protection is required. Typical installations include refineries, fuel transport terminals, offshore platforms, pipeline pumping stations, petrochemical plants, etc. Personnel safety combined with protection of large capitally intensive and often critical infrastructure necessitates uninterrupted operation of critical safety systems including fire/explosion detection and suppression.

Ultraviolet (UV) detection systems employ a quartz ion chamber to detect short, UV wavelength photons characteristic of most fires. UV systems respond to most fires, can be used indoors or outdoors, are generally
solar blind, and have high speed response times (<10 milliseconds). They are the most common general purpose optical flame detectors. Sensitivity to UV wavelengths photons means UV flame detectors are susceptible to false alarms from other sources: lightning, welding, arcs, sparks, and gamma rays/x-rays from radiographic testing (RT). RT can be particularly problematic due to the high photon energy relative to other sources of false alarms. Primary beam radiation incident on a UV detector in any orientation will likely trip the system as can Compton radiation scattered from the test piece or surrounding structures. Even flash dose as a source is projected from the shielded position through a source guide tube into a collimator, lasting at most a few seconds, is capable of tripping these high-speed detectors. Operators have several options to avoid false positives ranging from shutting down and manually monitoring UV flame detectors to forbidding RT altogether. One client reported shutting down and manually monitoring every detector within 0.5 miles (0.8 km) of RT work. The impact on plant operations and plant safety is readily apparent.

1.2 Nucleonic process control equipment (level, density, thickness, mass flow etc.)

Nucleonic process control equipment is found in many of the same installations as the optical flame detectors discussed above. Typical process monitoring applications include level gauging/switching, density measurement, thickness gauging, phase profiling, mass flow, etc. Nucleonic gauges generally do not contact process material and are thus ideal for high pressure, high temperature, corrosive, abrasive, caustic applications.

Nucleonic gauges operate in either transmission or backscatter mode. Transmission mode consists of a high-energy gamma ray source(s), typically $^{137}\text{Cs}$ or $^{60}\text{Co}$, either external to a vessel in a shield/collimator or internal to a vessel in a dip-tube with a detector(s) on the opposite side or other appropriate external position. Attenuation of the collimated beam varies with process material density, composition, or phase. In transmission mode, the detectors measure the uncollided gamma ray flux (i.e., gamma rays that have not been absorbed or elastically scattered). Low energy gamma emitting isotopes such as $^{241}\text{Am}$ along with beta emitting isotopes are used in transmission or backscatter mode for gauging of thin films, paper, foils, etc. As the name implies, backscatter mode measures radiation, often neutrons, that has elastically interacted with process material and scattered back to the detector. Transmission mode nucleonic gauges utilizing high energy gamma emitting isotopes are the most common systems impacted by RT and will be the focus of the following discussion. Several are shown in Error! Reference source not found. Error! Reference source not found.
As stated above, the uncollided gamma rays from collimated $^{137}$Cs and $^{60}$Co sources are measured to determine level, density, phases, etc. of process material in a vessel. Table 1 shows the similarity in gamma ray energies from common isotopes used in radiographic testing to those utilized in many nucleonic gauging systems. It is clear that gauging systems will have difficulties differentiating gamma rays from different sources and therefore be susceptible to false readings when RT is performed nearby. Compounding the issue is the significantly higher activity and resulting output of radiography sources versus gauging sources (see activity range and gamma constants in Table 1). Gauge manufacturers attempt to electronically filter direct beam and Compton scatter signals from high energy radiography sources (e.g., high frequency pulses from flash dose). Shielding detectors is an option complicated by the sometimes-large physical size and quantity of detectors (cost and space) as well as cooling requirements for stable operation of scintillation detectors common in gauging. Ultimately, solutions for operators to avoid costly and dangerous false readings include taking process control equipment offline – effectively driving blind or shutting down a line completely. The impacts on plant safety and operations are clear.

Table 1: Gamma ray energies from typical nucleonic gauging industrial radiographic testing isopopes. [1]

<table>
<thead>
<tr>
<th>Application</th>
<th>Isotope</th>
<th>Average Energy</th>
<th>Energy Range</th>
<th>Activity Range</th>
<th>Gamma Constant per Ci [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{137}$Cs</td>
<td>662 keV</td>
<td>662 keV</td>
<td>1 mCi – 10 Ci</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>$^{60}$Co</td>
<td>1253 keV</td>
<td>1.17 – 1.33 MeV</td>
<td>100 mCi – 10 Ci</td>
<td>14</td>
</tr>
<tr>
<td>Radiography</td>
<td>$^{75}$Se</td>
<td>215 keV</td>
<td>96.7 – 400.6 keV</td>
<td>10 – 120 Ci</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>$^{192}$Ir</td>
<td>370 keV</td>
<td>206 – 612 keV</td>
<td>10 – 150 Ci</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>$^{60}$Co</td>
<td>1253 keV</td>
<td>1.17 – 1.33 MeV</td>
<td>20 – 330 Ci</td>
<td>14</td>
</tr>
</tbody>
</table>

1.3 Radiation monitoring systems (NPP)

Nuclear power plants are particularly weary of introducing additional radiation and radioactive materials into operating environments; especially inside containment areas where HP officers are required to clear out other trades and monitor all RT operations for compliance with approved procedures. Deviations from procedure can trigger NRC reporting requirements. Seemingly innocuous events such as slight difficulty retracting a source, even if returned to a safe and locked position, are considered reportable events under 10CFR34.101 [3]. Another example of a reportable event under 10CFR20.2203 [4] would be flash dose or unanticipated scatter temporarily exceeding limits at posted boundaries.

1.4 Safety / Exclusion zone / Confined work areas / ALARA

In addition to the potential impact on safety and process control systems as describes above radiographic testing presents several other obstacles to plant safety and operations. Exclusion zones must be posted and controlled in accordance with regulations. In the USA exclusion zones are posted at 2 mR/hr (20 µSv/hr) for members of the general public. In much of the rest of the world exclusion zones are posted at 0.75 mR/hr (7.5 µSv/hr) for occupationally exposed workers and 0.25 mR/hr (2.5 µSv/hr) for members of the general
public. Posting and controlling exclusion zones becomes particularly problematic in congested work spaces such as a refinery turnaround where many trades are generally working in close proximity. In this scenario, other trades must either be cleared from the exclusion zone or RT crews must work in ‘shooting windows’ during breaks, shift changes, or third shifts. Radiography in confined or restricted access spaces increases ALARA and safety concerns. Radiographers must be able to move a safe distance from where the source is being exposed while also maintaining control of the system. Example application areas include offshore platforms, refinery turnarounds, rope access, fabrication shops, laydown yards, etc.

Minimizing the negative impact of gamma rays from radiographic testing is the focus of this discussion.

2 Understand to Control

SCAR or Small Controlled Area Radiography is the concept of controlling the radiation utilized for RT to minimize the impact on plant operations, increase plant safety, and improve safety for occupationally exposed workers and member of the public. Controlling the radiation used to perform radiographic inspection first requires an understanding of the mechanisms by which radiation interacts with the testing environment. We have found it useful to break down radiation we are looking to control into the primary beam and scatter radiation. Figure 4 visually depicts the primary beam and scatter radiation from a typical DW/SW radiography setup.

2.1 Primary Beam

The primary beam is a well-defined, collimated beam of gamma rays emanating directly from the isotope source. The collimated beam expands with increasing distance from the source. Shielding considerations are the intensity and cross-sectional dimensions of the primary beam at a specified distance where shielding material will be positioned (typically directly behind the imaging media). Calculations to determine shielding parameters for the primary beam are relatively straightforward. The number of shielding half value layers (HVLs) to reduce the primary beam intensity to a specified dose at a defined distance is a basic inverse square law shielding calculation outlined step-by-step in Figure 5. Note for a contact configuration where the beam width is smaller than the pipe diameter attenuation in the pipe can be considered. Figure 6 shows the determination of beam dimensions at the shielding position.
2.2 Compton Scatter

Compton scatter is significantly more complicated to model. For purposes of this discussion we consider a monoenergetic beam of gamma rays (energy = $E_0$). Three outcomes are possible for the incident gamma rays as they pass through matter: 1) pass through without interacting - the uncollided photon flux 2) absorption through pair production or the photoelectric effect 3) energy dissipating elastic scattering interactions with atomic electrons – Compton scatter. Figure 7 shows the combined effect of the three mechanisms on the beam spectrum. Absorption reduces the total number of gamma rays available to scatter or pass through without interaction. The uncollided flux was addressed above leaving scattered gamma rays as the second source of radiation to address. Energy loss in Compton scattering events is a function of interaction angle resulting in a continuous spectrum of photons with energy $E' < E_0$ into $4\pi$. In addition, Compton scatter is energy dependent interaction with the probability of an event occurring increasing with decreasing incident gamma ray energy. The practical takeaway is that Compton scatter complicates shielding setups as radiation is emitted in all directions; however, the scattered gamma rays are significantly lower in energy and intensity than the primary beam generally requiring fewer HVLs of shielding.
### 3 Achieving Small Controlled Area Radiography

It cannot be emphasized enough that SCAR is more than a radiography device. It is a radiography concept consisting of the radiography device and source, accessories such as positioning fixtures and shielding, and proper techniques to address both the primary beam and scatter radiation described above. The following section outlines these key components to achieving Small Controlled Area Radiography.

#### 3.1 Isotope

SCAR concepts are not exclusive to a particular isotope; however, the choice of isotope plays a key role in practical implementation of SCAR techniques. Average energy and energy ranges for typical radiography isotopes are summarized in Table 1. $^{75}$Se is by far the preferred isotope for SCAR applications due to the lower energy of its emissions relative to other available isotopes. When necessitated by material thickness SCAR techniques can also be applied to $^{192}$Ir radiography. To keep shielding practical $^{192}$Ir activities are kept low. As a comparison, consider the required shielding to obtain a 2 mR/hr reading 6 ft from the source in the direction of the primary beam shooting a 6” SCH 40 steel pipe in contact mode with both $^{75}$Se and $^{192}$Ir. Typical maximum activities for SCAR applications are 81 Ci and 15 Ci respectively. From Figure 5 and Figure 6 we calculate the weight of the back shielding to be 15 lb (7 kg) of lead sheet for 81 Ci $^{75}$Se versus 74 lb (33 kg) for 15 Ci $^{192}$Ir. Unless there is an extreme application, it is not practical to apply SCAR techniques for use with $^{60}$Co.

#### 3.2 Device

The radiography device is the next key component in achieving SCAR. In its simplest form, traditional projection style radiography involves projecting the source from the fully shielded position in the camera through an unshielded source guide tube to the test position where it remains for the duration of the shot and is then retracted back to the shielded position. The source is effectively completely unshielded from the moment the source leaves the camera to the time it returns (See Figure 8). For applications such as pipeline weld quality where other trades, sensors, members of the public, etc. are typically not present there is no issue with this technique. SCAR techniques would simply slow inspections down. However, in a refinery or power plant the large exclusions zones introduce myriad complications. For example, the 2 mR/hr boundary for 100 Ci of $^{192}$Ir is approximately 370 ft from the source. An ideal SCAR device minimizes the distance the source travels while never allowing the source to become fully unshielded, eliminating flash dose and simplifying shielding requirements. Below, we demonstrate exclusion zones of several feet with $^{75}$Se in a device specifically designed for SCAR.

![Energy spectrum of monoenergetic gamma rays incident on (dotted red) and exiting (solid blue) a shield.](image)
3.3 Fixtures and Shielding

The source does not leave the device in Figure 9. It moves from the fully shielded position directly to the collimated exposure position. Therefore, considerations should be made for allowing the radiographer to quickly and securely position and reposition the device in nearly any orientation. Figure 10 shows fixturing for a contact radiograph (e.g., DW/SW). Figure 11 shows fixturing for standoff fixturing for superimposed or elliptical radiographs. Mounting points for the fixturing are integrated into the design of the camera.

Shielding for radiography comes in many forms. The choice of material and form factor should be matched to the application and shielding requirements. Flat sheets for back shielding the primary beam and draping to control scatter range from simple lead sheets to lead wool blankets to silicone impregnated with a high Z material (e.g., lead, tungsten, or bismuth). Sheets can be bare or packaged in a protective sleeve. Some even have integrated rigging features or magnets to assist with positioning. There are pros/cons to each. Lead is a HAZMAT concern whereas bismuth and tungsten are not. Lead sheets are the most efficient and cost effective however lack flexibility. Lead wool blankets are also relatively inexpensive while offering increased flexibility over lead sheets but continuous flexing can degrade the fibres creating hot spots. Lead, tungsten, or bismuth impregnated silicone is extremely flexible but tends to be the priciest. Figure 12 shows examples of the several types of available shielding sheets.
3.4 Bringing it all Together

The above discussions walk through the concepts required to understand and consider in order to successfully achieve Small Controlled Area Radiography. While not overly complex, combining these concepts could easily become overly cumbersome in the fast paced and difficult radiography work environment. To simplify the process of determining a shot setup QSA Global has developed a SCAR Calculator (Figure 14) allowing the user to input readily available device and source data, dose requirements, and sample specifications. The calculator outputs the shot parameters: primary beam shielding requirements, primary beam dimensions, minimum source-to-film distance (SFD) from common geometrical unsharpness.
requirements, overlap to determine total number of shots, and shot time. Predictable and repeatable outcomes can be calculated for both contact and offset configurations.

Figure 14 considers a Model 1075 SCARPro loaded with 80 Ci $^{75}$Se shooting DW/SW contact of a 6” SCH 40 pipe. The 2 mR/hr boundary must be set at 6 ft. 2 Rad to the imaging media is required. The SCAR Calculator calculates a total of 11.3 HVLs are required to back shield the primary beam. The pipe itself provides 1.78 HVLs. An additional 9.5 HVLs are required. 3/8” (~1 cm) of lead sheet or four FlexShield sheets provide the required additional shielding. The beam is 6.7 in x 6.7 in (17 cm x 17 cm) at the film plane. Standard 10 in x 10 in (25 cm x 25 cm) in shielding sheets would be recommended for ease of positioning. A minimum of four shots are required to image the entire weld with 0.7” (1.8 cm) overlap. Shot time is 1 minute 21 seconds. A scatter shield (Figure 13) addresses the majority of the scatter off the near wall off the near wall of the pipe.

A 6 ft (~2 m) exclusion zone has clear benefits in many applications:

- Radiography can be performed in close proximity to other trades such as welders, pipe fitter, etc. during turnarounds or outages rather than clearing the area or shooting in windows.
- Nearby processes utilizing nuclear gauges or necessitating UV flame detectors can be left online and safely monitored.
- Rope access technicians (RATs) can minimize their exposure while remaining in close proximity to the test location.
• Monitoring and controlling a 6 ft boundary versus boundaries of several hundreds of feet for traditional projection radiography is much easier considering most plants have multiple floors. Common practices are to clear three floors up and three floors down anytime RT is being performed.
• Hot Work Permits issued and required by most plant safety managers are likely to be easier to obtain based on the vastly reduced zone of influence and repeatable setup geometries.

3.5 Additional SCAR Considerations

![Beam masking technique for offset SCAR configuration.](image1)

Figure 15: Beam masking technique for offset SCAR configuration.

The SCAR concepts discussed above apply to both contact and offset device configurations. Offset configurations are complicated by the increasing dimensions of the primary beam with increasing SFD. Back-shielding a large beam behind the imaging media can become overly cumbersome with inherently heavy shielding material. It is much more efficient to reduce the collimation or mask the beam very near the source. After all, the beam only needs to be wide enough and tall enough to image the diameter of the pipe/weld and heat effect zone in a weld quality radiograph. Figure 15 depicts the beam masking technique that allows for on-site adjustments to beam dimension.

![SCAR setup with shielding positioned over the end of a pipe segment to attenuate scatter internal to the pipe and wrapped around the length of the pipe near the test position to attenuate scatter out of a thin walled pipe. Scatter dose is 4 µSv/hr (0.4 mR/hr) at 2 m (6.6 ft) with 57 Ci $^{75}$Se source exposed.](image2)

Figure 16: SCAR setup with shielding positioned over the end of a pipe segment to attenuate scatter internal to the pipe and wrapped around the length of the pipe near the test position to attenuate scatter out of a thin walled pipe. Scatter dose is 4 µSv/hr (0.4 mR/hr) at 2 m (6.6 ft) with 57 Ci $^{75}$Se source exposed.

Some applications or highly regulated operating environments may necessitate additional shielding considerations. Figure 16 shows a SCAR setup with shielding placed at the end and along the lengths of an open-ended thin walled pipe to attenuate internal scatter and scatter along the length of the pipe.
4 Conclusion

SCAR concepts are well established in some regions of the world where regulations restricting operator and public exposure has driven its adoption (e.g., Europe). In other regions SCAR concepts and techniques have been applied for many years to address the issues described in this paper; with varying degrees of success. Where not driven by regulation, adoption of Small Controlled Area Radiography solutions often requires a paradigm shift both by radiography service providers and the industries they serve. Continual improvement to provide innovative, high quality solutions to customer pain points drives this paradigm shift. Service providers endeavour to address common pain points of their clients associated with radiographic testing. End consumers of RT services, often owners of highly capital intensive facilities, strive to minimize or eliminate anything adversely impacting operational efficiency. SCAR offers RT service providers a customer-back solution for their customers to minimize the impact of radiography on operations, enhance safety, and reduce overall operational liability often associated with industrial radiography.

References


