SAND2022-16871

SANDIA REPORT
SAND2022-16871
Printed December, 2022

Sandia National Laboratories

General Overview of Mobile Sources Used for Well Logging and Industrial Radiography Applications

Charles A. Potter, Jawad R. Moussa, Andrew Wilcox, Luke J. Gilbert, and Vanessa N. Vargas

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185
Livermore, California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@osti.gov
Online ordering: http://www.osti.gov/scitech

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: https://classic.ntis.gov/help/order-methods

ABSTRACT

Mobile sources is a term most commonly used to describe radioactive sources that are used in applications requiring frequent transportation. Such radioactive sources are in common use world-wide where typical applications include radiographic non-destructive evaluation (NDE) and oil and gas well logging, among others requiring lesser amounts of radioactivity. This report provides a general overview of mobile sources used for well logging and industrial radiography applications including radionuclides used, equipment, and alternative technologies. Information presented here has been extracted from a larger study on common mobile radiation sources and their use.

This page intentionally left blank.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Abbreviation	Definition
CoC	IAEA Code of Conduct on the Safety and Security of Radioactive Sources
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
D-T	Deuterium-Tritium
GMS	Global Material Security
IAEA	International Atomic Energy Agency
LWD	Logging While Drilling
NDE	Non-Destructive Evaluation
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NSDD	Office of Nuclear Smuggling Deterrence and Detection
ORS	Office of Radiological Security

1. INTRODUCTION

Mobile sources are radioactive sources that are used in applications requiring frequent transportation to job sites. Typical applications are radiographic non-destructive evaluation (NDE) and oil and gas well logging, among others requiring lesser amounts of radioactivity. These mobile sources are transported in a configuration that is easily moved on and off a truck-bed without requiring lifting gear. Because of the ease of movement of these sources and their amounts of radioactivity[1], use of these sources presents a risk of theft or loss, followed by some type of malicious use.

This report provides a general overview of radiation-based well logging technologies and industrial radiography devices. Information presented here has been extracted from a report written for a more comprehensive study which aimed to provide a better understanding of regional inventories and moving patterns of these types of sources [1].

[1] Sources are commonly above the IAEA Category 2 radioactivity threshold for radiography sources and just below the IAEA Category 2 threshold for well logging sources

2. MOBILE SOURCE APPLICATIONS OVERVIEW

There are a variety of mobile applications for radioactive sources in industry, agriculture, and other peaceful applications. Among those, industrial applications such as radiography, well logging, and density gauges are the most prominent. Some applications, such as density gauges, use small quantities of radioactive materials and, as such, are not considered to be a security concern. However, applications such as industrial radiography and well logging use radioactive sources up to the International Atomic Energy Agency (IAEA) Category 2 level, and if aggregated, could reach IAEA Category 1. In this chapter, a description of select mobile radioactive sources is provided.

2.1. IAEA Source Categorization

The source categorization used in the IAEA's *Code of Conduct on the Safety and Security of Radioactive Sources* (CoC) is based on the concept of *dangerous* sources, which are quantified in terms of *D values* [2, 3].[1] The categorization concept is further discussed in the IAEA's *Categorization of Radioactive Sources* [4]. In these documents, the IAEA provides a recommended unified international system of radioactivity-based source categorization, particularly for those sources used in industry, medicine, agriculture, research, and education. The system has five categories, which are sufficient to enable the practical applications of the scheme without unwarranted precision. Within this categorization system, sources in Category 1 are considered to be the most dangerous because they can pose a very high risk to human health if not managed safely and securely. An exposure of only a few minutes to an unshielded Category 1 source may be fatal. At the lower end of the categorization system, sources in Category 5 are the least dangerous. Categories should not be subdivided, as this would imply a degree of precision that is not warranted and could lead to a loss of international harmonization [5].[2]

2.2. Industrial Radiography

Similar to how medical x-rays are used to identify breaks in bones, industrial radiography is an NDE method that is used to inspect and evaluate the structural integrity and uniformity of materials and components using ionizing radiation. It is considered to be one of the oldest methods of NDE, which further evolved rapidly with the introduction of radioactive cobalt and iridium after World War II [7]. X-rays produced by x-ray generators or γ-rays produced by radioactive sources are the most commonly used forms of penetrating radiation in this application.

[1] The concept of danger, in this instance, refers to the possibility of succumbing to certain deterministic effects.

[2] Only Categories 1 – 3 have security measures required under the CoC and, in the United States (US), Title 10 Code of Federal Regulations Part 37[2, 6]

At a fundamental level, industrial radiography works by focusing a beam of ionizing radiation at an item of interest and aligning a detector, commonly photographic film, on the opposite side. The detector records the radiation that passes through the material, where fewer rays pass through thicker regions and more rays pass through cracks or flaws in the material. The resultant image is then used to identify any imperfections or defects in the material being inspected. Figure 2-1 illustrates the typical setup of an industrial radiography test.

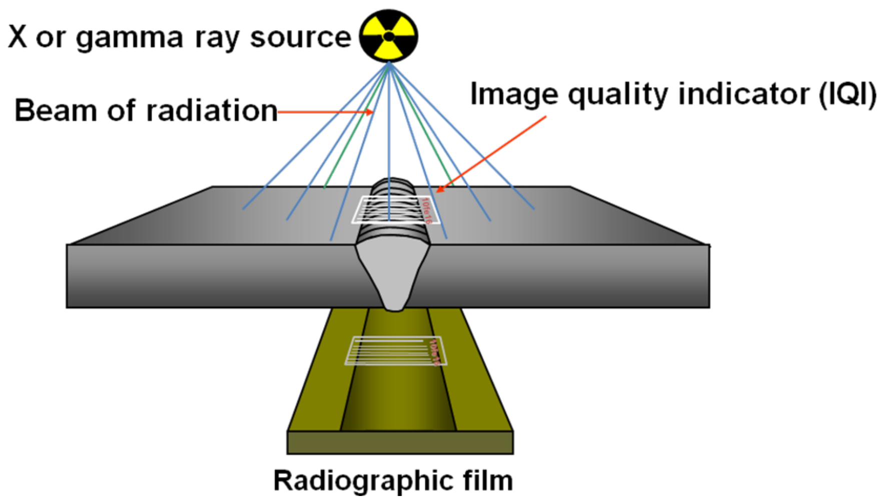


Figure 2-1. A typical industrial radiography setup [8].

X-ray and γ-ray devices differ in many aspects and tend to be used in different settings based on the specific application. For example, x-ray radiography devices rely on electricity, meaning they can be turned on and off with no x-rays being produced when the device is powered off. Such devices provide a reduced safety risk; however, they tend to be large, which limits their mobility. Factories and laboratory settings where a constant and reliable power supply is available for large batch operations are some of the most common places x-ray radiography devices are found. Conversely, γ-ray radiography devices do not rely on electricity because the γ-rays are produced from radioactive material located inside the device itself. This is an energy efficient characteristic that comes at the expense of not being able to power down such devices, since the radionuclides in the device will continue to produce γ-rays at a consistent rate. Designs for such devices include a dense metal (e.g., lead) shield to block the γ-rays while the device is not in use. Depending on the design and manufacturer, the need for shielding introduces an additional safety concern, as operators must be careful to retract the source into and close the shield when the radiography device is not in use to protect others from radiation exposure. Nevertheless, they are smaller in size as compared to x-ray radiography devices, making them much easier to transport and more practical for use inside small spaces and in the field environment.

The fragility of industrial radiography equipment is also an important consideration. Industrial radiographers are generally deployed to harsh industrial or outdoor environments. Hence, mobile γ-ray devices are preferred for such conditions for their rugged design and mobility. This introduces a security concern, as devices containing radioactive material are being transported from one location to another and being stored in transportation vehicles while not in use during off hours.

2.2.1. *Radionuclides Used in Industrial Radiography*

Only a select few radionuclides are commonly found in devices used for industrial radiography applications. These radionuclides are cobalt-60 (^{60}Co,) iridium-192 (^{192}Ir), and selenium-75 (^{75}Se). Other radionuclides that were mentioned in the literature but are rarely used are ytterbium-169 (^{169}Yb), cesium-137 (^{137}Cs), and thulium-170 (^{170}Tm). The choice of which radionuclide is used depends on many factors but is mostly driven by the type and thickness of the material being inspected. Hence, it is important to have some understanding of the range at which the γ- or x-rays produced will penetrate the material — a characteristic that is measured by the average energy of the emitted radiation and the *half-value thickness* (the thickness that shields one-half of the incident photons) for a given radionuclide. Table 2-1 provides these values for the listed radionuclides.

Table 2-1. Average energy of emitted γ-rays and half-value thickness in millimeters of lead for common industrial radiography radionuclides [7].

Radionuclide	Symbol	Average Energy (MeV)	Half-Value Thickness (mm of Pb)
Cesium-137	^{137}Cs	0.66	8.4
Cobalt-60	^{60}Co	1.25	13
Iridium-192	^{192}Ir	0.45	2.8
Selenium-75	^{75}Se	0.32	2
Ytterbium-169	^{169}Yb	0.2	1
Thulium-170	^{170}Tm	0.072	0.6

Other factors that may influence the choice of radionuclide include:

- Building codes and regulations [3]
- Material density and geometry
- Operational location
- Employee safety and operations
- Customer preference

What follows is a summary of where each of the three most commonly used radionuclides can be found and comparative properties.

Cobalt-60. Industrial radiography cameras based on ^{60}Co are reserved for extremely thick or dense materials, like concrete, or 2.5 to 5-inch-thick steel, because of its high energy γ-rays. The shielding required for ^{60}Co industrial radiography cameras make these devices cumbersome and heavy. Further, cobalt cameras require larger controlled areas that may extend to several floors (>300 ft) and significantly impact site operations.

[3] Interviews indicated that MIL-STD-271 Rev F. and SAE AMS-STD-2175 are particularly influential in determining the radionuclide used [9, 10]

Iridium-192. Industrial radiography cameras based on ^{192}Ir sources are the most versatile, as ^{192}Ir γ-rays have three times the penetrating power compared to ^{75}Se and cameras are more mobile than those using ^{60}Co. Regulatorily-controlled areas for ^{192}Ir radiography are also much smaller than those for ^{60}Co, 100–150 ft to 300 ft for newly reloaded cameras. Iridium-192 cameras are used for larger pipes (> 4 in diameter).

Selenium-75. Selenium-75 is preferred for small pipes, as the softer (i.e., less energetic) γ-rays generally produce a better image on x-ray film. While ^{75}Se γ-rays have one third the penetration of those for ^{192}Ir, ^{75}Se cameras require less frequent source reloading due to longer half-life. The use of ^{75}Se is preferred for its reduced controlled area requirements (as low as 20 ft). Selenium-75 is specifically requested for use in nuclear reactors, as the controlled area minimally impacts site operations, safety, and security.

2.2.2. Industrial Radiography Applications and Equipment

Industries such as petrochemical and gas, construction, automotive and transportation, and manufacturing are a few examples of where industrial radiography is commonly used. All employ industrial radiography for a variety of applications. Perhaps one of the main reasons it is considered a key tool for quality control, safety, and reliability is its ability to identify internal cracks or flaws that are otherwise not visible to the naked eye, without damaging or changing the item being tested. In addition, it can be used at times when it is difficult to access the material being inspected. Some common applications of industrial radiography are:

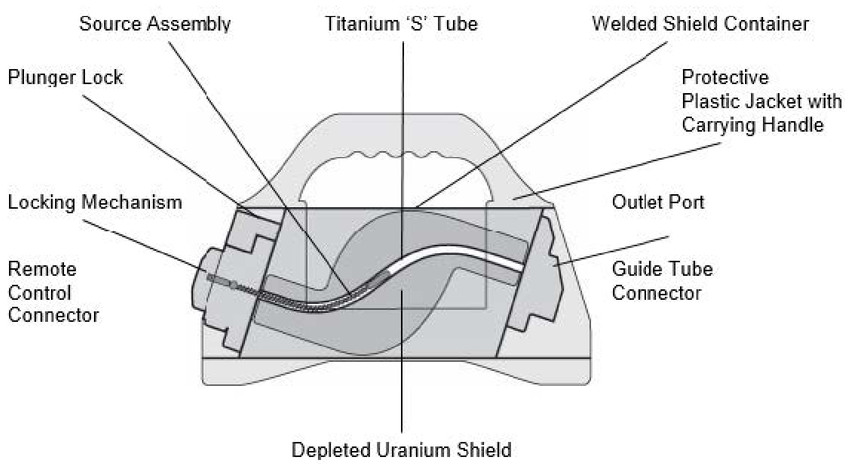
- Inspecting the welds of pipelines and pressure vessels in the petrochemicals and gas industry;
- Monitoring and regulating equipment according to standard values at manufacturing plants in the mining industry, metal industry, and pipe and tube manufacturing; and
- Inspecting the integrity of rebar reinforcements during building construction to ensure they are continuous and intact.

The typical equipment for mobile industrial radiography applications is a portable exposure device, also referred to as a *radiography camera*. An example of a typical radiography camera is shown in Figure 2-2a.

For example, the QSA Sentinel 880 series consists of a stainless-steel housing containing a depleted uranium shield, locking mechanism, outlet port, and protective covers. The inside structure and major components are shown in Figure 2-2b. As described in *880 Series Gamma-ray Source Projector and Transport Container*, the QSA manual for that device:

> Standard Ir source assemblies contain metallic ^{192}Ir discs or pellets which are doubly encapsulated in welded stainless steel or titanium capsules. The sealed sources are designed and tested to achieve an ISO/ANSI minimum classification of 97C64515 and to comply with the IAEA and US Department of Transportation (DOT) requirements for *special form* radioactive material. The ISO/ANSI classification 97C64515 stated in this manual refers to the source capsule which is attached to the source assembly. This

(a) Outer view.



(b) Inside construction.

Figure 2-2. QSA SENTINEL 880 industrial radiography camera [11].

Table 2-2. Commercially available industrial radiography devices [12, 13, 14, 15, 16]. Values are of amount of radioactivity (Ci) in typical device.

	^{60}Co	^{192}Ir	^{75}Se	^{169}Yb	^{137}Cs
Sentinel 880 Delta Source Projectors	0.065	150	150	108	-
Sentinel 880 Sigma Source Projectors	0.025	130	150	30	-
Sentinel 880 Elite Source Projectors	0.025	150	150	108	-
Sentinel 880 Omega Source Projectors	-	15	80	108	-
SENTRY Series 110	110	-	-	-	-
SENTRY Series 330	330	-	-	-	-
741 A/B Projector	33	-	-	-	-
680 A/B Projector	110	-	-	-	-
Sentinel 1075 SCARPRO Source Projectors	-	-	81	-	-
979 Crawler Head	-	-	0.025	-	-
SENTINEL 959M Scar Projector	-	15	81	-	-
865 Projector	-	240	-	-	-
INC IR-100 Gamma Ray Camera	-	120	120	-	-
SPEC-150	-	150	150	-	-
SPEC-300	300	-	-	-	-
SPEC-Se120	-	-	81	-	-
Viking II	-	2	81	81	1
Viking IV	-	27	81	81	1
Viking X	-	27	81	81	1
Viking CPR	-	-	54	54	1

classification also applies to the ^{75}Se, ^{60}Co and ^{137}Cs versions of the source assemblies [11].

A list of radiography devices available through open-source literature is provided in Table 2-2, along with the radionuclides used and associated activity.

2.2.3. Industrial Radiography Operational Logistics

The typical life cycle of an industrial radiography device consists of several distinct steps that are described in detail in this section and are shown in the graphic in Figure 2-3.

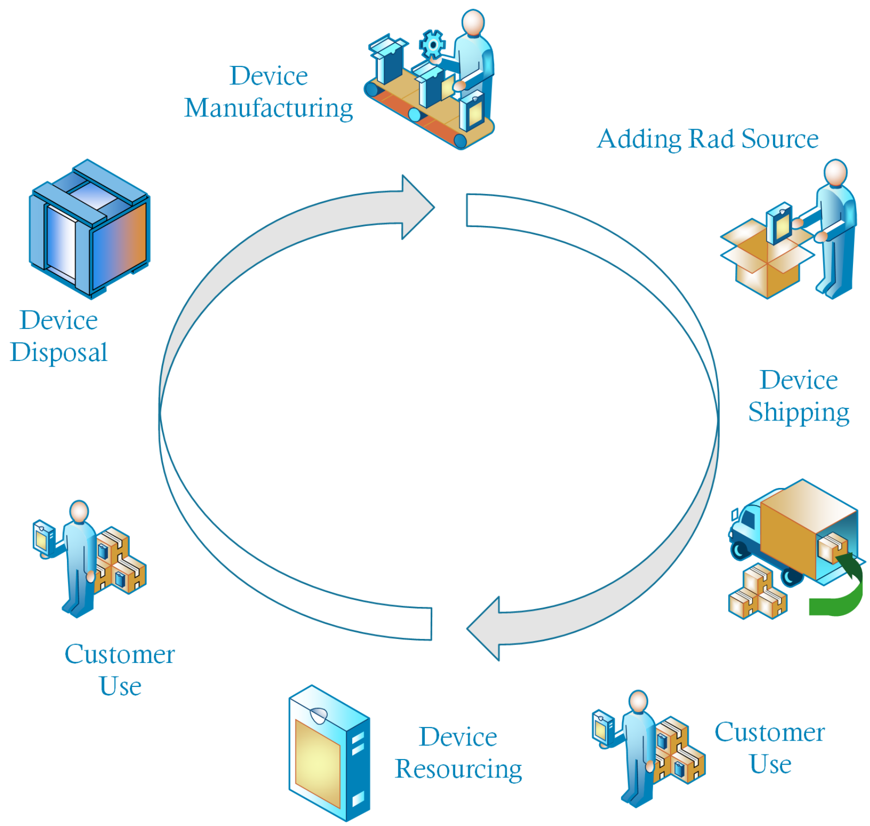


Figure 2-3. Typical industrial radiography device life cycle.

Device manufacturing: First, the device is manufactured at the manufacturer's facility and is quality tested according to regulations and codes. The manufacturing process is dependent on the type of source and it's application. For example, Ir and Se projectors are lead-shielded containers with internal mechanisms to extend and retract the source, while well logging devices are polyethylene shielded balls that hold the source until needed. No special security arrangements are needed at this step since radioactive sources are not present.

Adding rad source: Once the device is manufactured and tested, it is fitted with an appropriate radioactive source. This step usually takes place in the manufacturer's facility, where a number of sources are stored, and appropriate safety and security measures are implemented.

Device shipping: Manufactured and sourced devices are then shipped to the customer either domestically or internationally. In the U.S., a manufacturer needs an export license from the U.S.

Nuclear Regulatory Commission (NRC). Shipping traditionally is performed by major commercial vendors, such as FedEx[4] or DHL;[5] there are no or minimal security arrangements during transport.

Customer use: This is the stage of normal operation for an industrial radiography device. Once received by the customer, the device is used for mobile measurements and inspections. While in the customer's possession, most national regulations require inspection and maintenance at quarterly intervals. Complete annual servicing, performed by the manufacturer or qualified user, ensures the integrity of the device. Shorter frequencies of inspection and maintenance are required when the device is operated in severe operating environments. In some cases, the device should be serviced immediately after certain jobs in harsh environments [11].

Device resourcing: Once the source in a device decays to the level of activity that does not provide the desired performance, the device must be *resourced*. There are two ways this is usually done. The first is for the device owner to ship the device to the manufacturer to perform the procedure at the production facility. This often happens in the U.S. domestically, and is a requirement for ^{60}Co sources. The other option is for new sources to be shipped to the customer and for the process to be done at the customer's facility. In the latter case, the used sources are shipped back to the supplier or directly to the disposal site. Internationally, especially in the Southeast Asian region, most end users are using local source suppliers to resource their devices instead of ordering from U.S. manufacturers.

Device disposal: Industrial radiography devices have a fairly short designated lifetime, which depends on the conditions and frequency of use. The inner-tube and the locking mechanism are especially prone to wear and tear. Traditionally, most of the components, especially the depleted uranium shielding, are recycled and used in production of new devices. It has been noted during interviews that devices supplied to Southeast Asia sometimes are used years and, in some cases, decades over their designated or suggested lifetime increasing the risk that a source may be lost outside of the device.

2.2.3.1. Operational Safety Approaches for Field Measurements

As stated previously, industrial *field* radiography is performed when the material being examined cannot be moved to a shielded facility. Examples include areas like refineries, pipelines, offshore platforms, welding fabrication shops, and building construction sites where portable exposure devices are used for performing industrial radiography. The planning of site work depends on the location of specimen being examined, time of the day, the weather conditions, and the presence of non-radiation workers in the area.

[4]FedEx Corporation, Memphis, TN
[5]Deutsche Post DHL Group, Bonn, GE

The following steps are usually included in the process of performing industrial field radiography:

- Exposure planning—length of shot, location, angle, etc.
- Preliminary radiation safety performance checks
- Controlled area setup
- Radiographer dose monitoring

The radiographer and radiography assistants must wear an integrating dosimeter (e.g., thermoluminescent dosimeter) and a self-reading dosimeter with a range of 0–2 mSv (0–200 mRem) at all times. Regulatory requirements in the U.S. also require an audible alarm ratemeter be worn at temporary jobsites. The radiographer should confirm that people are excluded from the areas where radiation hazard is present, and a special audible signal should be used when the source is about to be exposed. A different signal, often a beacon, should indicate the exposed source position.

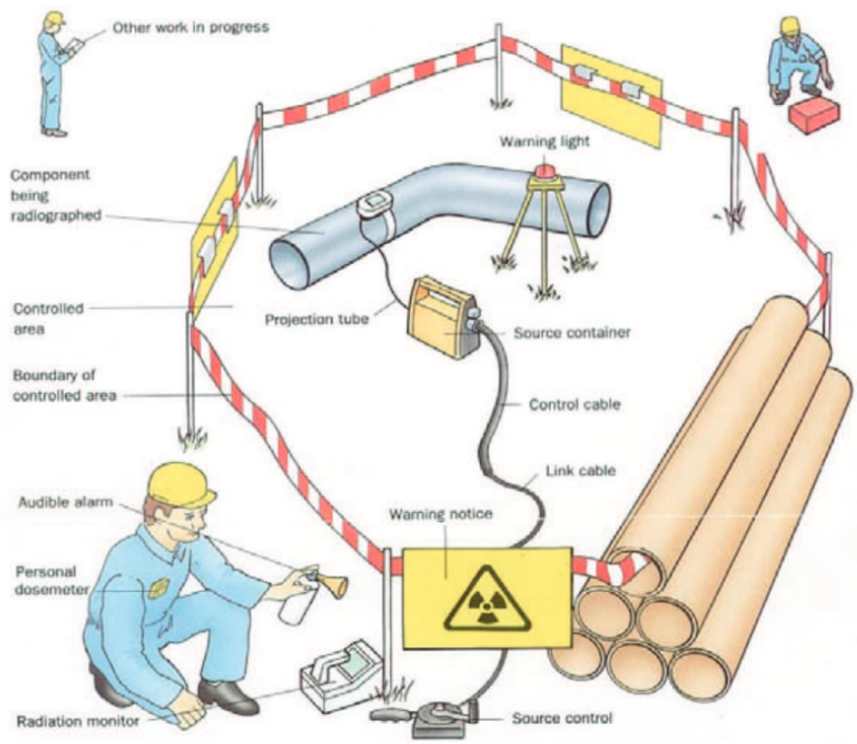


Figure 2-4. Industrial radiography site safety precautions [17].

All exposure devices should be stored when not in use. There are many requirements for radiation source storage facility, which can vary from country to country based on national regulations. Below is the summary list of most typical conditions desired for radiation source storage facilities [7].

An exposure device storage facility should:

- Be located under the jurisdiction of the licensee, such that it shall not allow access to the general public
- Be equipped with a security monitoring system
- Be provided with locking devices and arrangements to limit access to authorized personnel only
- Be clearly labeled with radiation warning signs including the name, address, and telephone number of the delegate responsible user
- Be constructed using fire resistant materials
- Be used only for storing exposure devices
- Be monitored for radiation dose levels using a survey meter at all times

2.2.3.2. Industrial Radiography Economic Considerations

The costs of radiography services are structured on a per-hour basis. Often, it is the customers who decide on the type of the source and minimum activity to be used for their particular needs.

The worldwide market for industrial radiography was approximately $532 M in 2020 and is expected to achieve a compound annual growth rate of 8.1%, thereby increasing to $784 M by 2025. The drivers for this industry-wide expected growth include [18]:

- Increased international government regulations regarding industrial safety
- Global demand for consumer electronics requiring additional quality testing
- Rapid technological advancements driving an increased manufacturer focus on research and development

2.2.4. Alternative Technologies for Industrial Radiography

Industrial radiography is a mature inspection method with the following limitations [7]:

- Industrial radiography requires access to both sides of the specimen
- Radiographic film used in the development process is sensitive to visible light
- The geometry of the specimen can become a challenge for inspection
- Industrial radiography is a radiation hazard
- Industrial radiography has a limited thickness range for material examination

X-ray radiography is currently the main non-source-based alternative technology used in industrial radiography. A study conducted by Sandia for the National Nuclear Security Administration's (NNSA) Office of Radiological Security (ORS) in 2021 has shown that most NDE providers have a mixed γ-ray and x-ray-based instrumentation. However, it is the customers who usually dictate the choice of equipment to be used based on their cost and performance requirements. The overall conclusion of the study was that it is unlikely that x-ray-based devices would be able to replace currently existing radioactive source-based industrial radiography devices in the near future [19]. Nevertheless, other NDE methods exist, such as acoustic emission and ultrasonic thickness measurement, that can be used in lieu of industrial radiography. Figure 2-5 provides a list of imperfections and compares the effectiveness of several NDE methods in detecting them.

	Surface [Note (1)]		Sub-surf. [Note (2)]		Volumetric [Note (3)]				
	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT
Service-Induced Imperfections									
Abrasive Wear (Localized)	●	◑	◑		●	◑	◑		◑
Baffle Wear (Heat Exchangers)	●			◑					
Corrosion-Assisted Fatigue Cracks	○	◑	●		○	●		●	
Corrosion -Crevice	●								○
-General / Uniform				○	◑		◑		●
-Pitting	●	●	○		●	○	○	◑	○
-Selective	●	●	○						○
Creep (Primary) [Note (4)]									
Erosion	●				●	○	◑		◑
Fatigue Cracks	○	●	●	◑	◑	●		●	
Fretting (Heat Exchanger Tubing)	◑			◑					◑
Hot Cracking		◑	◑		◑	○		◑	
Hydrogen-Induced Cracking		◑	◑		○	◑		◑	
Intergranular Stress-Corrosion Cracks						○			
Stress-Corrosion Cracks (Transgranular)	○	◑	●	○	◑	◑		◑	
Welding Imperfections									
Burn Through	●				●	◑			○
Cracks	○	●	●	◑	◑	●	○	●	
Excessive/Inadequate Reinforcement	●				●	◑	○		○
Inclusions (Slag/Tungsten)			◑	◑	●	◑	○	○	
Incomplete Fusion	◑		◑	◑	◑	●	◑	◑	
Incomplete Penetration	◑	●	●	◑	●	●	◑	◑	
Misalignment	●				●	◑			
Overlap	◑	●	●	○		○			
Porosity	●	●	○		●	◑	○	○	
Root Concavity	●				●	◑	○	○	○
Undercut	●	◑	◑	○	●	◑	○	○	
Product Form Imperfections									
Bursts (Forgings)	○	●	●	◑	◑	◑	◑	●	
Cold Shuts (Castings)	○	●	●	○	●	◑	◑	○	
Cracks (All Product Forms)	○	●	●	◑	◑	◑	○	●	
Hot Tear (Castings)	○	●	●	◑	◑	◑	○	○	
Inclusions (All Product Forms)			◑	◑	●	◑	○	○	
Lamination (Plate, Pipe)	○	◑	◑			○	●	○	●
Laps (Forgings)	○	●	●	○	◑		○	○	
Porosity (Castings)	●	●	○		●	○	○	○	
Seams (Bar, Pipe)	○	●	●	◑	○	◑	◑	○	

Legend:
AE – Acoustic Emission
ET – Electromagnetic (Eddy Current)
MT – Magnetic Particle
PT – Liquid Penetrant
RT – Radiography
UTA – Ultrasonic Angle Beam
UTS – Ultrasonic Straight Beam
UTT – Ultrasonic Thickness Measurement
VT – Visual
● – All or most standard techniques will detect this imperfection under all or most conditions.
◑ – One or more standard technique(s) will detect this imperfection under certain conditions.
○ – Special techniques, conditions, and/or personnel qualifications are required to detect this imperfection.

GENERAL NOTE: Table A-110 lists imperfections and NDE methods that are capable of detecting them. It must be kept in mind that this table is very general in nature. Many factors influence the detectability of imperfections. This table assumes that only qualified personnel are performing nondestructive examinations and good conditions exist to permit examination (good access, surface conditions, cleanliness, etc.).

NOTES:
(1) Methods capable of detecting imperfections that are open to the surface only.
(2) Methods capable of detecting imperfections that are either open to the surface or slightly subsurface.
(3) Methods capable of detecting imperfections that may be located anywhere within the examined volume.
(4) Various NDE methods are capable of detecting tertiary (3rd stage) creep and some, particularly using special techniques, are capable of detecting secondary (2nd stage) creep. There are various descriptions/definitions for the stages of creep and a particular description/definition will not be applicable to all materials and product forms.

Figure 2-5. List of common imperfections and the NDE methods that are used to detect them [20]

2.3. Well Logging

Well logging employs multiple technologies, with and without the use of radioactive sources, to accurately obtain geologic information. Physical, acoustical, and electrical properties are obtained by taking measurements within a borehole [21]. While there are multiple non-radiologic well logging methods, three major radiological technologies exist: a density porosity tool typically using γ-rays emitted from ^{137}Cs; a neutron porosity tool typically employing americium-241/beryllium (^{241}Am/Be) neutron sources; and neutron absorption and carbon/oxygen tools, which require 14.1 MeV neutrons from Deuterium-Tritium (D-T) neutron generators [21]. Well logging techniques were first employed in 1926 with the invention of electrical well logging, which was used to measure the resistivity of the geologic formation as a method to prospect for metal ore deposits in subsurface locations [20]. Radiological well logging was developed out of a desire to measure natural radiation from formations and progressed to using γ-radiation, and later neutrons, to determine the porosity of the subsurface media. It has become a very sophisticated method that is used routinely in well drilling for hydrocarbon exploration, oil field development, and monitoring. In a field with high operational expenses, well logging is seen as an essential tool to accurately determine geologic information and assess the safety of a well formation. Using well logs, data can be interpreted to determine where rock formations, oil reservoirs, and water tables are in the immediate vicinity. The use of well logs also provides environmental and general safety to the user and the area of land that is being drilled. They provide information so that water tables are not contaminated with oil or chemicals from fracking [22]. Salt formations are avoided because they will collapse the borehole [21]. Well logging also provides useful information to support the academic understanding of geophysics.

Well logging is usually performed either after a borehole has been drilled, known as wireline logging, or while the well is being drilled, known as Logging While Drilling (LWD) [20]. When wireline drilling is performed, the various instruments are strung together on a cable with an electronic signal wire. The measurements are made and transmitted in real time to the surface where the data is logged. This technology can also be used less reliably after a well has been cased, which means it is no longer being drilled and a protective shell, generally of steel, has been placed in the hole. In LWD, the instruments are placed along the drill, and information on the location and direction of the drill head is gathered, along with formation features of the rock [23]. This is done while drilling is being performed, though the data is transmitted at a lower rate than wireline logging. The use of well logs can increase oil or gas recovery and result in safer drilling. Generally, this data is taken at intervals of 3 and 15 cm [20]. For both wireline and LWD, these instruments are attached to conductor cable to transmit data. In wireline well logging, a "bow spring centralizer" is attached to the instruments. This is a device that presses on the walls of the borehole, keeping the instruments stable as they collect their data in order to keep measurements accurate [24].

2.3.1. Radionuclides Used in Well Logging Applications

The primary radionuclides used in well logging for porosity measurement in geologic formations are Category 4 ^{137}Cs sources for density measurement and Category 2 ^{241}Am/Be neutron sources [23]. Since 2018 the U.S. domestic use of ^{241}Am has begun to decrease, primarily due to major well logging companies' investments in alternative technologies (such as deuterium-tritium neutron generators), a reduction in oil and gas exploration, and a push to move toward renewable energy solutions. There is little data to be found on international trends; however, it is assumed that this drop domestically is representative of future trends worldwide [25]. There has been a downward trend, 40% domestically from 2013 to 2020, in the overall use of ^{137}Cs sources in all applications, which is also due to x-ray technology replacement efforts being made by ORS. It is unclear how this trend will affect the prevalence of ^{137}Cs in well logging; however, the decline of the oil and gas industry will likely reduce demand.

Cobalt-60 sources are used in the drilling process for determination of depth of the measured log and drill but is not used in well logging itself. Plutonium beryllium (PuBe) sources[6] have been used in the past as an alternative to ^{241}Am/Be sources, and californium-252 (^{252}Cf) sources have been demonstrated to be a potential replacement as well, though they have not been used in practice [20]. Passive radiological sources found naturally in geologic formations are also used for logging data by collecting the background emissions from said formations, but they will not be considered in this report as they are not related to the risk of theft.

Table 2-3. Radionuclides used in well-logging applications [19].

Isotopes	Radiation Type	Measurement	Activity Range (Ci)
^{241}Am/Be	Neutron Source	Porosity	3-20
^{137}Cs	High Energy Gamma Source	Density	>2.5Ci

In well logging ^{241}Am/Be sources are generally Category 2 sources with activities of about 4–20 Ci, and ^{137}Cs sources are generally Category 4 sources at activities found to be 1.5–2 Ci [20].

A list of source manufacturers can be found in the 2020 Argonne National Laboratory Sealed Source Marketplace Study [25].

2.3.2. Equipment

γ-ray equipment: When density is measured using γ-backscatter, the wireline or drill is equipped with a γ-ray source in vitrified form. Two sodium iodide (NaI) scintillator detectors are placed on either side of the source with photo-multiplier tubes attached to each one (see Figure 2-6). The spectra and γ-ray density are logged. Using a series of equations, the intensity of the γ-ray is related to the Compton scattering attenuation coefficient, then to the bulk density of the formation, and finally to the porosity of the formation. There are other factors that need to be corrected for while the tool is in the borehole, such as the mud that accumulates along the side of the instrument while drilling is occurring. Liquid is squeezed out of the mud to cool the drill and forms a solid "cake" where the source and detector are taking measurements. The density and thickness of the mud need to be corrected for to attain an accurate reading. Barite can also be present in the drilled mud, and due to its very high atomic number, it can attenuate the γ-rays emitted from the source [26].

[6] Unlike AmBe sources containing ^{241}Am, PuBe sources include a range of Pu isotopes from 238–242. Each isotope, to some extent, also produces neutrons through spontaneous fission.

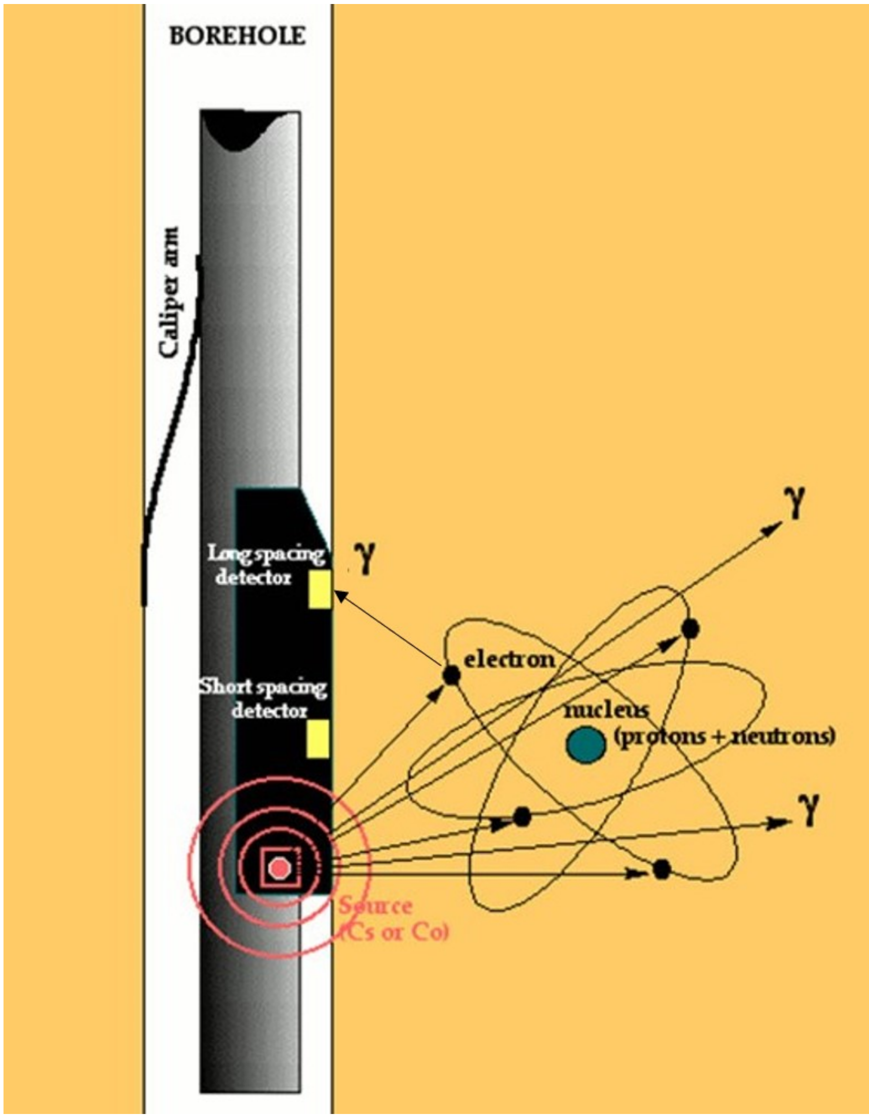


Figure 2-6. Gamma density well-logging tool [27].

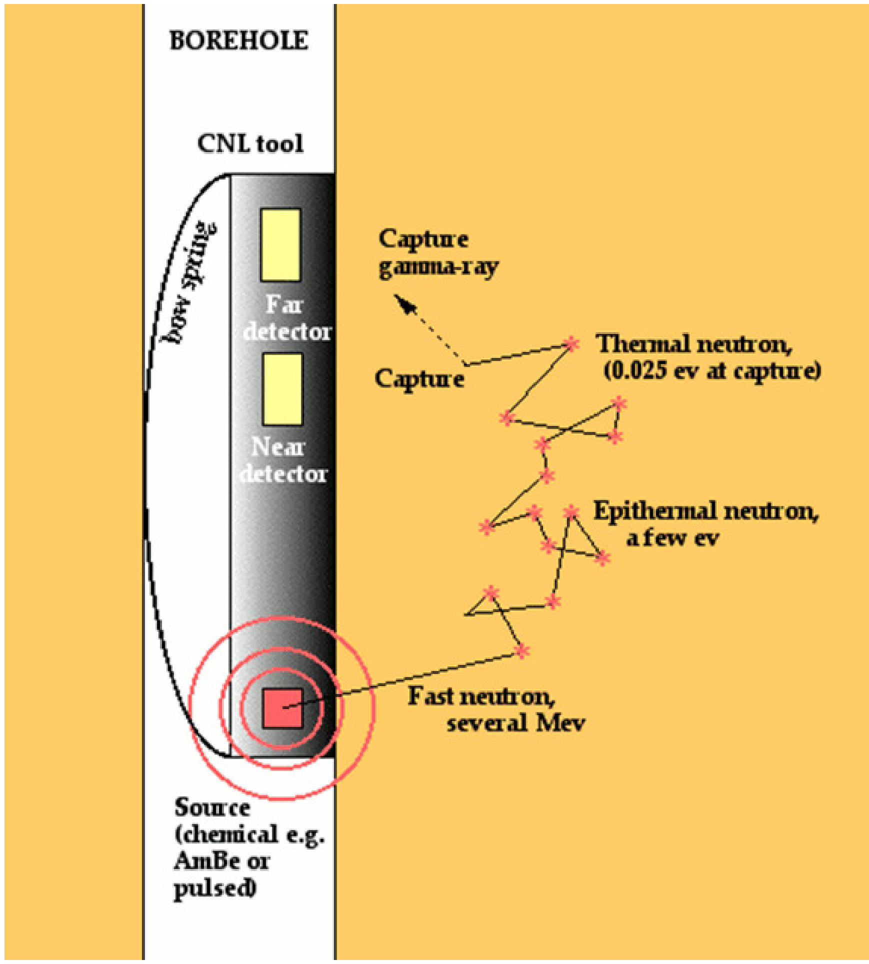


Figure 2-7. Neutron porosity well-logging tool [27].

Neutron equipment: A neutron source is pressed and encased in stainless steel. The wireline or drill is equipped with the neutron source and two helium-3 (^{3}He) detectors are placed above it (see Figure 2-7). The closer detector is labeled the "near detector", and the farther detector is labeled the "far detector". This configuration is used to reduce environmental effects that would be seen by a single detector. Each detector count is taken as a ratio of near to far counts (N/F). This ratio is then related to the neutron porosity of a lithology in porosity units. These measurements' accuracy can be complicated by atom density in the formation, clay formations, and gases [28]. Increase in atom density increases neutron scattering, reduces the neutrons that are able to be detected, and increases the measured porosity. Clays also increase the porosity measurements. When a gas is present, the porosity measurements can be reduced or even read as negative [26].

When the γ-ray and neutron sources are not in use, they are removed from the equipment using source handling tools and are stored in transport containers.

2.3.2.1. Well Logging Operational Logistics

The purchase of a well logging device for international use requires the receiving company to obtain a license through the vendor company. This license is granted in accordance with the regulations for carriers by land, rail, sea, inland waters, and air relating to the requirements of local governments. Transportation of equipment domestically is regulated by the U.S. NRC, U.S. DOT regulations 10 CFR part 20 and 71 [6]. Well logging equipment that is shipped without sources is transported in trucks or mobile laboratories. The sealed sources are taken out and transported separately in specified transport containers. Alternatively, the device and source can be shipped together, where the source is doubly enclosed within cylindrical capsules made of stainless steel. The source is attached within the inner capsule using a stainless-steel sleeve, and each capsule is welded shut using a tungsten inert gas weld. The outer capsule is marked with an engraving of the serial number, nuclide, radiation warning, and the manufacturer's identification mark. International transportation is guided by IAEA Safety Standards Series No. SSR-6, Regulations for the Safe Transport of Radioactive Material; regulations concerning the International Carriage of Dangerous Goods by Rail; International Maritime Dangerous Goods Code; and Ordinance on the National and International Carriage of Dangerous Goods by Land [29, 30, 31, 32]. Leak testing of sources must be performed no longer than six months before transportation and must have yielded a negative result.

As an example of the licensing process, a ^{137}Cs well logging device was supplied by Sensor Technology AS [7] to TechnipFMC Oil and Gas,[8], at an activity of 0.03 Ci. This device was then licensed to Eckert and Ziegler Nuclitech GmbH[9] through TechnipFMC, in accordance with the licensing requirements defined above for 80,000 NOK[10] or approximately 9,200 USD. In this case, the licensee was neither the manufacturer (Sensor Technology) or the user (Eckert & Ziegler), but the intermediary owner, TechnipFMC [33].

2.3.3. Alternative Technologies for Well-Logging

Currently D-T, deuterium-deuterium, and tritium-tritium neutron generators, producing a 2.5, 14.1, and 11.3 MeV neutrons respectively, are already being used for neutron absorption and carbon/oxygen ratio analysis [34]. Schlumberger [11] is also marketing D-T neutron generators as a replacement for ^{241}Am/Be source tools in both elemental analysis and nuclear porosity analysis, though this technology is subject to more strict regulations by the U.S. Export Administration and could incur greater costs and delays [20]. Californium-252 has been suggested as a replacement for ^{241}Am/Be sources but there has been little investigation into them in the well-logging field, and the short half-life of only 2.45 years would require them to be replaced frequently [20]. Similarly, Compton

[7] Sensor Technology AS (S-Tec), Sarpsborg, Norway
[8] TechnipFMC plc, Newcastle Upon Tyne, UK
[9] Eckert & Ziegler Strahlen- und Medizintechnik AG, Berlin, GE
[10] Norwegian kroner
[11] Schlumberger, Houston, TX

scattering methods using electrically generated x-rays have been considered; however, the reliability and convenience of ^{60}Co and ^{137}Cs sources have kept well logging operators from becoming concerned with the replacement of these radionuclides.

3. SUMMARY AND DISCUSSION

The use of mobile radiation sources is common worldwide despite ongoing efforts to replace these sources with non-source alternatives (*alternative technology*). For some applications, however, using radiation sources is the only way of accomplishing the desired outcome. Activities for which mobile sources are in greatest use are industrial radiography and oil well logging.

This report has been extracted from a greater study and provides a general overview of mobile source devices, typical lifecycle, operational logistics, and emerging technologies, which are limited and not likely to replace source-based devices any time soon [1].

Section 2.2 provides detailed information on radionuclides used in industrial radiography including ^{75}Se, ^{60}Co, and ^{192}Ir. Additional rarely used radionuclides are ^{137}Cs, ^{169}Yb, and ^{170}Tm. Some sources can be of significant activity greater than IAEA Category 1 and 2 thresholds, indicating requirements for security of the sources. A list of commercially available industrial radiography devices was compiled from open-source literature and is provided. Limitations of industrial radiography were discussed along with some common NDE alternatives. Alternative technologies for industrial radiography are not very common; choice of technology and radionuclide is often driven by the demand of the customer. In addition, x-ray devices rely on a consistent power source, allowing them to be turned on and off. This makes them less of a risk, but their large size limits their mobility, while γ-ray sources do not rely on power, meaning they will continue to emit γ-rays at a constant rate. This introduces an additional safety concern, but their smaller size and mobility makes them more favorable operationally than x-ray devices.

Section 2.3 describes the well logging application. In this application, Category 4 amounts of ^{137}Cs and Category 2 amounts of ^{241}Am as AmBe sources are employed. The team was unable to get interviews from well logging companies but was able to collect some information from open sources. For this application, the adoption of alternative (neutron generator) technologies would require possibly significant up-front data collection and analysis, because the neutron spectrum from a neutron generator is quite different than that from an AmBe source. The user would have to gain an understanding of the data "picture" provided by the device.

Mobile radioactive sources are in common use worldwide. The security of such sources is dependent on the strength of the regulations in the country in which they are in use. It remains important that sources are treated responsibly throughout their lifecycle.

REFERENCES

[1] Charles Potter et al. *[Title Withheld]*. Sandia Report. Albuquerque, NM: Sandia National Laboratories, Feb. 2022.

[2] International Atomic Energy Agency. *Code of Conduct on the Safety and Security of Radioactive Sources*. Non-serial Publications IAEA/CODEOC/2004. Vienna: International Atomic Energy Agency, 2004.

[3] International Atomic Energy Agency. *Dangerous Quantities of Radioactive Material (D-Values)*. Emergency Preparedness and Response EPR-D-VALUES 2006. Vienna: International Atomic Energy Agency, 2006.

[4] International Atomic Energy Agency. *Categorization of Radioactive Sources*. General Safety Guides RS-G-1.9. Vienna: International Atomic Energy Agency, 2005.

[5] International Atomic Energy Agency. *Security of Radioactive Material in Use and Storage and of Associated Facilities*. Implementing Guides NSS-11-G (Rev.1). Vienna: International Atomic Energy Agency, 2019.

[6] Nuclear Regulatory Commission. "10 CFR Parts 20, 30, 32, 71, et al. Physical Protection of Byproduct Material; Rule". In: *Federal Register* 78.53 (Mar. 19, 2013). Part II, pp. 16922–17022.

[7] G.W. Jaques and A.U. Rehman. *A Practical Field Handbook in Industrial Radiography and Radiograph Interpretation*. George's River, NS, CA: Jaques Enterprise Inspection Inc, 2019.

[8] TWI. *TWI Radiography*. URL: `https://www.twi-global.com/technical-knowledge/job-knowledge/radiography-124` (visited on 10/21/2021).

[9] U.S. Department of Defense. *Requirements for Nondestructive Testing Methods*. Military Standard MIL-STD-271F(SH). U.S. Department of Defense, June 27, 1986.

[10] Society of Automotive Engineers. *Classification and Inspection of Castings*. SAE Standard SAE AMS-STD-2175. Society of Automotive Engineers, July 1, 2003.

[11] QSA Global. *880 Series Gamma-ray Source Projector and Transport Container. Operations and Maintenance Manual*. MAN-027. May 2021.

[12] QSA Global. *SENTINEL™ 880 Series Gamma-Ray Source Projectors*. URL: `https://www.qsa-global.com/880-series-gamma-ray-source-projectors` (visited on 05/01/2020).

[13] INC. Industrial Nuclear Co. *The INC IR-100 Gamma Ray Camera Key Benefits*. URL: `http://www.ir100.com/products/gamma-radiation-projection-devices/` (visited on 05/01/2020).

[14] Gilligans. *Viking Products*. URL: `https://gilligans.co.uk/viking-products/` (visited on 05/01/2020).

[15] Inc Source Production & Equipment Co. *Radiography Equipment*. URL: http://www.spec150.com/radiography-equipment/ (visited on 05/01/2020).

[16] NDT Equipment Sales. *GAMMA INSPECTION AND X-RAY EQUIPMENT*. URL: https://www.ndt.com.au/product-category/x-ray-gamma-inspection/page/2/ (visited on 05/01/2020).

[17] International Atomic Energy Agency. *Industrial Radiography. Radiation Protection of Workers*. poster. May 3, 2011. URL: https://www-ns.iaea.org/tech-areas/communication-networks/orpnet/documents/Industrial-Radiography.pdf (visited on 01/25/2022).

[18] MarketsandMarkets Research. *Industrial Radiography Market. Industrial Radiography Market by Imaging Technique (Film-based Radiography, Digital Radiography), End User (Petrochemicals & Gas, Power Generation, Manufacturing, Aerospace, and Automotive & Transportation), and Geography - Global Forecast to 2025*. Mar. 2020. URL: https://www.marketsandmarkets.com/Market-Reports/industrial-radiography-market-249604981.html (visited on 01/25/2022).

[19] J.D. Patrick, R.W. Swinney, and G. Wagner. *IR-Camera Replacement with Portable X-Ray Study*. Sandia Report SAND2021-10822. Albuquerque, NM: Sandia National Laboratories, Sept. 2021.

[20] National Research Council. *Radiation Source Use and Replacement: Abbreviated Version*. National Academies Press, 2008.

[21] Paul W.J. Glover. “Petrophysics, Chapters 9–15”. In: *University of Aberdeen, UK* (2000).

[22] International Atomic Energy Agency. *Radiation Safety in Well Logging*. Specific Safety Guide SSG-57. Vienna, 2020.

[23] Luke Leyland. *The Importance and Application of Well Logging*. 2021. URL: https://medium.com/@welllogging/the-importance-and-applications-of-well-logging-3fe97fd1fa0e (visited on 08/23/2017).

[24] NRC Human Resources Training and Development. *Well Logging Photo Overview and Accident Scenarios*. URL: https://www.nrc.gov/docs/ML1122/ML11229A041.pdf. (accessed: 2021-08-17).

[25] Argonne National Laboratory. *Sealed Source Marketplace Study: 2020 Update*. Argonne Report. Lemont, Illinois, 2020.

[26] Lawrence Livermore National Laboratory. *Scoping Study on Developing Alternatives to Radionuclide-based Logging Technologies*. Lawrence Livermore Report LLNL-TR-679101. Livermore, California, 2015.

[27] Kansas Geologic Survey. *Nuclear Logging*. URL: https://www.kgs.ku.edu/Publications/Bulletins/LA/04_nuclear.html (visited on 07/31/2017).

[28] Scott. *Neutron Porosity Logging Revisited*. URL: https://www.slb.com/-/media/files/oilfield-review/p04-08 (visited on 08/15/2020).

[29] International Atomic Energy Agency. *Regulations for the Safe Transport of Radioactive Material*. Safety Guide SSR-6. Vienna: International Atomic Energy Agency, 2018.

[30] Economic Commission for Europe Inland Transport Committee. “Agreement Concerning the International Carriage of Dangerous Goods by Road”. In: *United Nations Economic Commission for Europe* 1 (2020).

[31] International Maritime Organization. “International Maritime Dangerous Goods Code”. In: *The International Convention for the Safety of Life at Sea* (Jan. 1, 2020).

[32] RID Safety Committee and the Working Party on the Transport of Dangerous Goods. “Agreements governing the Regulations Concerning the International Transport of Dangerous Goods by Rail (RID)”. In: *UNECE Transport Divison* (Oct. 6, 2020).

[33] Eric Rasmussen. (TechnipFMC) in discussion with the authors. Jan. 13, 2022.

[34] Leonard J. Bond et al. *Evaluation of Non-Nuclear Techniques for Well Logging*. Tech. rep. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2011.

DISTRIBUTION

Email—Internal

Name	Org.	Sandia Email Address
Technical Library	1911	sanddocs@sandia.gov

This page intentionally left blank.

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.