9.4 Nuclear Gauges

Today many industries use equipment that incorporate a radioactive source as a measuring gauge. Nuclear gauges provide an inexpensive, yet highly reliable and accurate method of measuring the thickness, density, level, or make-up of a wide variety of materials and surfaces. There are two types of nuclear gauges, fixed and portable.

9.4.a Fixed Gauges

*Fixed gauges* are most often used in factories and other industrial settings as a way of monitoring a production process and ensuring quality control. In many processes, either products cannot be effectively checked by traditional methods which normally requires direct contact, or a nondestructive measuring technique is desired. In these situations, a nuclear gauge can be inserted into the process to provide precise measurements of thickness, density, or level.

These fixed gauges consist of a radioactive source that is housed within a source holder and placed at a crucial point in the process. When the source holder's shutter is opened (Figure 9-6), a beam of radiation is directed at the material being processed. A detector mounted opposite the source measures the radiation that passes through the material. A readout either on the gauge or on a connected computer terminal registers the required information (e.g., the thickness of a product as it passes between the source and the detector, the level of liquid in a bottle as it is being filled, the level of molten glass in a furnace [Figure 9-7], the moisture content of wood chips,
etc.). The passage of radiation does not cause any change in the material, and the material itself in no way becomes radioactive.

Fixed gauges are commonly used in many types of processing environments from mills to breweries. These gauges are so sensitive they are even used in paper mills where they measure the thickness of a sheet of paper as it leaves the presses. In breweries fixed gauges insure that each bottle contains the right amount of beer. Thus, whatever the application, fixed gauges ensure quality control in a process.

9.4.b Portable (Moisture / Density) Gauges

Portable gauges are used in industries such as agriculture, construction, and civil engineering to measure things like the moisture in soil or cement and the density of asphalt in a paving mix. There are several basic methods of measuring material with portable gauges: direct transmission, backscatter, moisture and thin layer (Figure 9-8).

Direct Transmission is considered the more precise of the two, as it has less error in measuring composition and compensates for surface roughness. The gamma source is positioned at a specific depth within the test material by inserting it into an access hole. Gamma rays are transmitted through the test material to detectors located within the gauge. The average density between the gamma source and the detectors is then determined based upon how much radiation was shielded. Direct transmission is used for testing medium to thick lifts of soil, aggregate, asphalt, and concrete. Thus, this system can be used at construction sites to measure soil density after compacting.

The backscatter method eliminates the need for an access hole by allowing both the source and detector to remain on the surface. Radiation is directed beneath the surface. Some radiation is reflected or scattered back to the gauge’s detector by the material near the surface. This method is usually less accurate than direct transmission, because of the large scattering angle and shallow depth of measurement. It is also insensitive to density variations beyond a depth of two to three inches. However, the backscatter method is quicker and easier than direct transmission and is useful when measuring thin layers of uniform material such as asphalt paving and concrete.

The moisture measurement is nondestructive with the neutron source and detector located inside the gauge, just above the surface of the test material. Fast neutrons enter the test material and are slowed after colliding with the hydrogen atoms present. The detector in the gauge counts the number of thermalized (slowed) neutrons, which relates directly to the amount of moisture in the sample.

The thin layer process is a special modification of the backscatter method designed to measure the density of asphalt and concrete overlays from 1 - 4 inches (2.54 - 10.16 cm) without influence from underlying material.

Source Strength

Each portable moisture / density gauge uses one or two sealed radioactive sources (e.g., americium-241, cesium-137, krypton-85, americium-241/beryllium, radium-226, Californium-252, or cobalt-60 -- Figure 9-9). The source’s strength is measured in terms of how many radioactive decay events there are (see 1.2.d). Although these sources are physically quite small, they are often extremely powerful and highly radioactive. Sources used in moisture density gauges are normally americium-241/beryllium. Americium-241 is an alpha emitter. When beryllium absorbs an alpha particle, it becomes excited and emits a neutron of approximately 4.5 MeV.

\[
\begin{align*}
241\,\text{Am} & \rightarrow 237\,\text{Np} + \frac{4}{2}\,a + 5.48\,\text{MeV} \\
& \rightarrow 2\,a + 9\,\text{Be} \rightarrow 12\,\text{C} + \frac{1}{0}\,n
\end{align*}
\]
The efficiency for this process is rather low, approximately $60 \times 10^{-6}$ neutrons per second per becquerel (or $2.22 \times 10^6$ neutrons per second per curie) of $^{241}$Am. Because a buildup of helium gas within the capsule could rupture the capsule, these sources are leak-tested every 6 months to insure source integrity. In moisture/density gauges, the $^{241}$Am source is nominally 1850 MBq(50 mCi), emitting approximately 110,000 neutrons per second. However, remember the quality factor (Table 1-4) for neutrons is between 2 - 10, depending upon energy, so precautions are necessary to keep exposures ALARA.

Workers are protected from receiving excess radiation by the source shielding, by proper handling techniques, and by the fact that the U.S. Nuclear Regulatory Commission has performed a safety evaluation of all nuclear gauges in the United States to ensure that, under proper use, they will pose no radiation hazard. Note that a small amount of radiation always penetrates the gauge housing and can be detected by a radiation survey meter even if the source capsule is intact. This low level radiation poses no measurable health risk. The following section outlines the many ways in which the possible hazards associated with nuclear gauges are minimized.

9.4.c Proper use of Portable Nuclear Gauges

Working with and around (portable) nuclear gauges is no different than working with other types of industrial equipment, certain rules and procedures must be followed to ensure safe use. Always follow the operating procedures provided by the manufacturer and Radiation Safety. When handled in accordance with these guides, the radioactive materials present no hazard to employees, customers, or the general public.

Radiation Safety Office

Use and possession of portable gauges (Figure 9-10) is under the direction and supervision of the University’s Radiation Safety Office (RSO). The RSO is a single point of accountability and responsibility between the State Radiation Protection Branch and the gauge user. The RSO is responsible for all aspects of gauge radiation safety, insuring that:

- all terms and conditions of the license are complied with and that the license information contained is up-to-date and accurate.
- the equipment is inventoried and leak tested at least semiannually, as specified in the UW's radioactive license.
- the equipment is used only by operators trained and authorized by the RSO, that they use the equipment in accordance with applicable regulations and they are wearing appropriate personnel dosimeters (Chapter 7).
- records required by the license and the regulations are properly maintained.
- all equipment is properly secured against unauthorized removal at all times.
- all required signs and notices are properly posted at gauge storage location.
- all operators have read and understand this Radiation Safety Plan.
  - State of Wisconsin, Department of Health & Family Services, PPH Form 45027, Notice to Employees.
  - temporary storage areas labeled with "Caution - Radioactive Material" signs.
  - notice posted of where a copy of the UW license, safety plan, and copy of regulations are located.

The RSO also serves as a point of contact and gives assistance in case of an emergency such as equipment damage in the field, theft, or fire and to notify the proper authorities in case of an emergency and arrange appropriate training for all operators.

Operators

Operation of this type of gauge is often away from the main campus of the UW, either at a field station or other remote site. The UW's radioactive material license specifies that sealed sources in portable nuclear gauges may be
used at temporary job sites of the licensee anywhere in the State of Wisconsin. Out of state use is not authorized. Use on land not owned by the University of Wisconsin should be performed only after written permission has been obtained from the owner.

- The operator will exercise suitable control over the gauge at all times. At no time is it to be left unattended or in the possession of an untrained or unauthorized person.
- When not being used to make field measurements, the gauge will be locked and returned to its storage / transportation case.
- When testing is complete, the gauge will be returned to its permanent place of storage as soon as possible. When storage is required at a temporary field site, the room will be locked and posted with Caution - Radioactive Materials signs.
- After completing the daily measurements and upon return of the gauge to its storage location (either temporary or permanent), check to insure that the gauge is not damaged, perform a radiation survey of the gauge in its shipping case, and document the results in the gauge’s use log. Contact the RSO immediately if unexpected exposures are measured; insure that the source is retracted into its safe, storage position, but do not attempt to dismantle or repair the source.
- When using the gauge, the operator must wear their assigned personnel dosimeter (TLD). When the operator is not using the equipment, the monitoring device will be kept in a radiation-free area.
- At all times, operators will observe ALARA principles to minimize any dose received.
- While the equipment is in the operator’s possession, the operator will have copies of:
  - the UW’s radioactive material License
  - the Radiation Safety Plan with Emergency Procedures and Telephone Call List
  - the gauge’s operating manual
  - a current Leak Test Certificate
- The Operator will conspicuously post all required signs and notices at any temporary storage location.

Transportation
Safety in the transportation of radioactive materials depends on proper packaging and on the efficient manner in which the packages are handled, stored and transported. Nuclear gauges are transported in Type A packages (see Chapter 8). Type A packages normally contain relatively small quantities of radioactive materials and therefore are required to withstand only the normal rigors of transportation. To be in compliance with the regulations, such packages must be able to withstand drop, penetration, compression and vibration tests, as well as exposure to extreme climatic conditions that are encountered in normal transportation. Each shipper is required to maintain on file the results of the package testing. Licensees who transport gauges to and from temporary job sites in licensee or private vehicles are shippers acting as private carriers and, as such, must comply with DOT regulations governing both shippers and carriers, 49 CFR Parts 170 - 178 (see Chapter 8).

- During transportation, the gauge must be secured in the transporting vehicle and located away from personnel. When transported in a closed vehicle (car or van), the case will be locked and the vehicle will be locked when the operator is not with the vehicle. When transported in an open bed vehicle (pickup truck), the case will be locked and the case securely fastened and locked (e.g., chained) to the truck bed when the operator is not with vehicle.
- The equipment can only be transported in its approved DOT shipping container with all the required labels and markings.
- During transportation the operator must have shipping papers on the seat beside the driver or in a holder which is mounted to the inside of the door on the driver's side of the vehicle describing the radioactive material with the proper nomenclature. Sample shipping papers are included with each gauge’s Radiation Safety Plan packet.
- When shipping by common carrier (e.g., Federal Express), the package shall be in compliance with 49 CFR Parts 170 - 179 and, if appropriate, IATA. Call Safety, 2-8769, for details.

Maintenance
Only the manufacturer of the gauge, or a person authorized by the NRC or an Agreement State, should attempt to repair the source, source holder, or shutter. Periodic maintenance (e.g., cleaning the gauge) is an operator function. The operator will have received proper instruction on how to clean the gauge and will wear any assigned monitoring device. If necessary when using a nuclear gauge in the field, clean the area around the shutter throughout the day.

- Always lock the shutter in the "off" position until maintenance is completed and avoid any physical contact with, or direct exposure to the source when performing any maintenance.
A leak test is be performed semiannually by the RSO in accordance with the gauge manufacturer's instructions. If in the field for a prolonged period, the operator will receive proper instruction on how to leak test the gauge and will wear all assigned monitoring devices.

Check the shipping case periodically for integrity and to verify that all labels are present and readable.

No maintenance will be performed in which the radioactive source is removed from the gauge. The gauge will be returned to the manufacturer or an approved service center for this type of service.

Storage
When not issued to an authorized operator, sources are permanently stored in a location designated by the RSO. When in use, sources will be stored either in an on-campus, approved location or at a temporary location near the job site. Besides performing a receipt survey (see 8.5) and insuring the required signs are posted (e.g., Caution - Radioactive Materials), the following guidance should be considered when selecting a temporary storage room.

- Separate rooms, locked and posted are preferable, however, a metal or wooden cabinet is acceptable if it can be locked and posted.
- Gauges should be placed so they are stored a minimum 10 feet from any occupied work areas.
- Room or cabinet should include appropriate electrical outlets to charge the meter's power supply.
- No more than two gauges should be stored in the same temporary location unless the distance to occupied areas is increased.

Before storing the gauge the operator must insure the gauge is intact and radiation levels are appropriate. This is done by inspecting the gauge and insuring that the gauge is not physically damaged. Because the gauge is considered a sealed radioactive source that is in transit between uses, the operator must perform a radiation survey (see 8.5) of the gauge in its shipping case. Since the gauge is a sealed source, wipe tests / contamination surveys are not required, only radiation exposure measurements are required. Measure the exposure rate in mR/hr at the package surface and at 1 meter (3.3 feet) and record the survey results in the gauge's use log. If unexpected or high exposures are measured, call the RSO immediately.

Records
The records accompanying a gauge consist of personnel monitoring, leak test results, training certificate, and gauge inventory. A check out log is normally assigned to each gauge. Information on the log includes gauge serial number, operator checking out gauge, date checked out, destination, estimated return date, and actual date of return.

Training
All operators must complete an operator's training course tailored by the RSO for gauge work in general. Special training by the operator's faculty advisor may also be required for an operator's individual work assignments.

Emergency Procedures
The Radiation Safety Plan packet includes DOT required emergency procedures and a plan of action in case of an accident or in the event of damage to the gauge. If you are uncertain about what to do should a malfunction, accident or damage occur, take the following steps:

- Stop work immediately
- If the gauge has been partially damaged or destroyed, keep people at least 20 feet away until the source is replaced or shielded, or until radiation levels are known. The survey meter supplied with the gauge can be used to measure radiation levels.
  - ✓ If moving equipment is involved, stop any movement and evaluate the extent of contamination, if any.
  - ✓ Cordon off the area around the incident. An area with a radius of twenty (20) feet will be sufficient.
  - ✓ Visually inspect the gauge to check the extent of the damage to the source, source housing, and shielding.
  - ✓ At the earliest possible time after the situation is under control, contact the RSO. Describe the conditions and follow the instructions of the RSO.
- In the event of a fire, call the fire department. Take appropriate action to protect personnel. Stand by to advise the fire fighters as to the nature, locations, and potential hazards of the radioactive materials. If available, supply the firefighters with an information packet consisting of the facility layout and a data sheet of the equipment which includes a photograph or sketch of the gauge. Be sure to include any other important information, e.g., explosives, guard dogs, etc. Temperatures in an industrial fire will normally range from 500 °F at floor level to a high at the ceiling of 1400 °F to 1800 °F. The polyethylene and lead in the gauge and gauge shipping case would melt in most fires, the aluminum only in a severe fire. The stainless steel capsule would not reach its melting point.
Have a leak tests performed after any incident that may result in source damage.
- After an accident or fire, do not use the gauge until any danger from or damage to the source is checked.
- Immediately notify the UW Radiation Safety Office (608-262-8769) of any theft, accident, fire or other incident involving the gauge. The RSO will notify (as appropriate) the State Radiation Control Section, the Nuclear Regulatory Commission and the police.

Nuclear gauges present no major health danger if basic precautions outlined here are taken and common sense is used. By following proper procedures, the basic principles of radiation protection (see Chapter 4), and by insuring all operators and gauge users do likewise, you will be assured that your workplace is a safe one.

9.5 X-Ray Fluorescence (XRF)
Recall from Chapter 1 (Figure 1-13), each element is capable of emitting x-rays characteristic of that element's electron structure. If a gamma-ray ejects a k-shell electron from lead (shell energy ~ 88 keV), that electron is normally replaced by an electron from the l-shell (energy ~ 15.8 keV). A characteristic x-ray of about 72 keV would be emitted from the transition. In XRF, an energetic gamma ray source (e.g., $^{109}\text{Cd}$; $E_\gamma = 88$ keV) is used to produce characteristic x-rays within a sample. The XRF unit incorporates a small detector (Figure 9-12) that precisely measures the energy of the characteristic x-ray and determines both the element and amount.

XRF units are usually hand-held. The source is requires a radioactive material license. Often the manufacturer will sell the device as under a general license where the manufacturer holds the license and the user agrees to maintain the source according to the manufacturer's instructions which will includes leak test provisions.

9.6 Review Questions - Fill-in or select the correct response.
1. Irradiators are devices containing ________________.
2. The primary beam is always shielded in ________________ irradiators.
3. The primary beam is not shielded during the use of ________________ irradiators.
4. ________________ and ________________ are two potential hazards from irradiators.
5. ________________ are devices to prevent exposure to the source.
6. When using a Mark-I irradiator, ________________ and ________________ indicate the radiation source is in the OFF position.
7. The Mark-I irradiator source stuck alarm indicates that high / normal levels of radiation are in the room.
8. When using a JL-109 irradiators, pushing the ________________ button will interrupt sample irradiation.
9. Two types of nuclear gauges are ________________ and ________________.
10. Portable gauge users must also pass the transportation exam and comply with the DOT. true / false
11. Portable gauges are transported in Type A packages and must be stored in posted areas. true / false
12. If a gauge has been damaged, keep people at least ________________ feet away from the gauge.
13. Immediately notify Radiation Safety (262-8769) of any incident involving nuclear gauges. true / false

9.7 References
Campbell Pacific Nuclear, Soil Moisture Gage Radiation Safety Plan
JL Shepherd and Associates, Mark I 137Cesium Irradiators, JL Shepherd & Associates, San Fernando, CA
Nuclear Regulatory Commission, NUREG / BR-0133, Working Safety with Nuclear Gauges, Washington, D.C.