The Case of the
MISPLACED RADIOACTIVE ELEMENT

By Mitch Ricketts

Math Toolbox is designed to help readers apply STEM principles to everyday safety issues. Many readers may feel apprehensive about math and science. This series employs various communication strategies to make the learning process easier and more accessible.

Workers in many industries may be exposed to ionizing radiation from sources such as industrial and medical imaging devices, medical therapy units, nuclear reactors, moisture sensors, density meters and sterilization units (IAEA, 2006; 2020). Chronic low-level overexposures to ionizing radiation are known to cause an increase in the incidence of immune system suppression, cataracts and cancer. Acute high-level exposures may cause these same effects, with the possibility of additional injury such as radiation burns, radiation sickness, cardiovascular disease, stroke, digestive disease, respiratory disease, various blood diseases and even death.

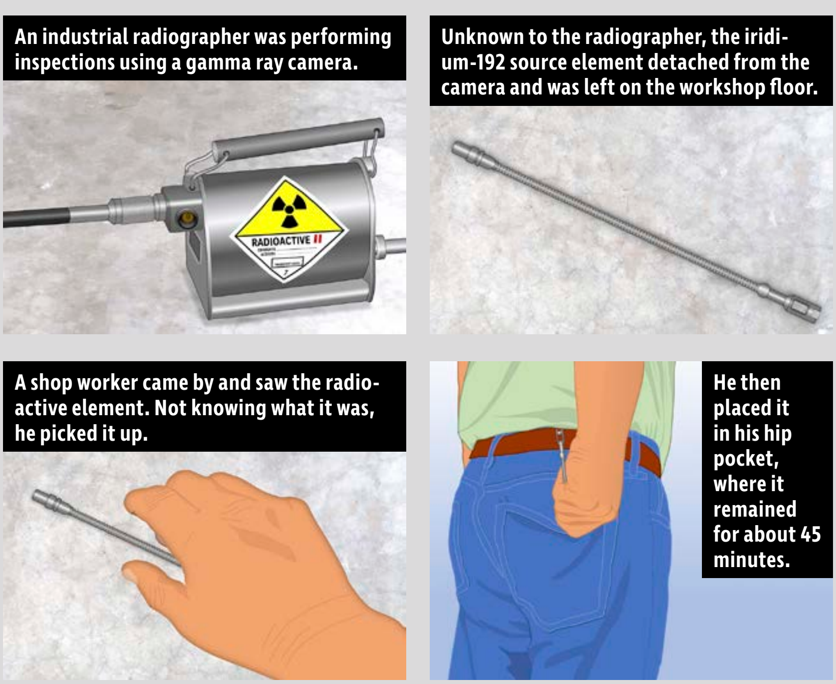
Figure 1 illustrates the details of a well-studied case of acute overexposure to gamma radiation from the unshielded radioactive element of an industrial radiography camera. Although this case occurred more than 40 years ago, the U.S. Nuclear Regulatory Commission (NRC, n.d.) continues to report numerous instances of worker overexposures caused by unshielded radiography elements and other sources.

It is not possible to specify a safe level of exposure to ionizing radiation, so it is generally recommended that exposures be kept as low as reasonably achievable (IAEA, 2018). OSH professionals achieve this goal through three main strategies: 1. using shielding to block the transmission of radioactive energy; 2. keeping radioactive sources a safe distance from workers; and 3. limiting the time that workers may be exposed. In the case illustrated in Figure 1, workers became exposed because the radioactive element became separated from its shielded enclosure. The exposure caused the most severe health effects in workers who were closest to the source for the longest period.

This article focuses on the second concern: The distance of workers from the unshielded radioactive element. We will examine this concern from the perspective of the inverse square law, an equation that helps determine the intensity of radiation based on distance from a source.

FIGURE 1

UNSHIELDED RADIOGRAPHY ELEMENT CAUSES SEVERE RADIATION BURNS, LOS ANGELES, CA



Soon, the shop worker became nauseated. A few hours later, a severe radiation burn began to develop on his right buttock. The burn became ulcerated, creating a wound with a diameter of about 4 in. and nearly an inch deep. Extensive reconstructive surgery was required to close the wound.

Other workers who briefly handled the source at the time of the incident developed radiation burns on their fingers.

Note. Adapted from "1979 Los Angeles Accident: Exposure to Iridium 192 Industrial Radiographic Source," by J.F. Ross, F.E. Holly, H.A. Zarem, C.M. Rothman & A.L. Shabo, 1980, in K.F. Hubner & S.A. Fry (Eds.), The Medical Basis for Radiation Accident Preparedness (pp. 205-221). Elsevier/North-Holland.

Inverse Square Law for Point Sources of Gamma & X-Rays

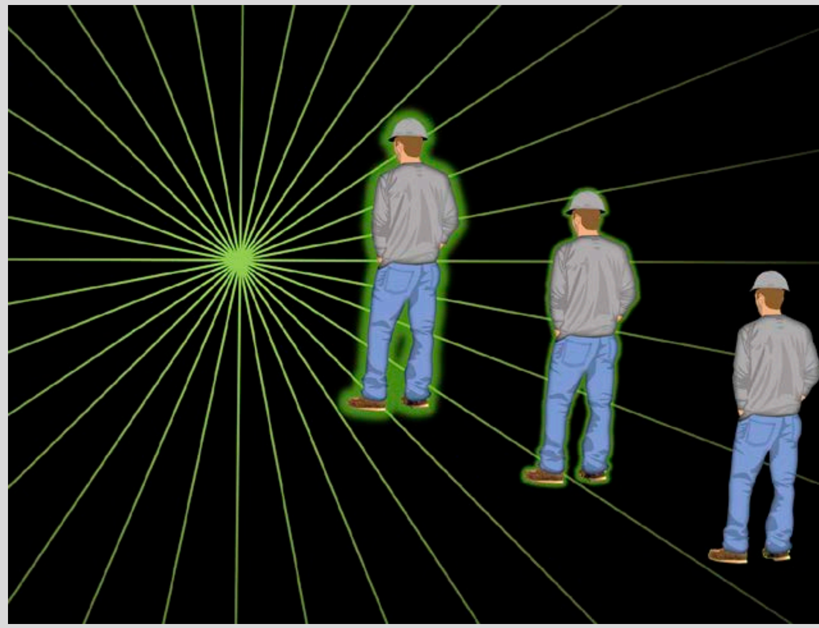
The inverse square law is based on the observation that radiation becomes less intense the farther away one moves from the source. Figure 2 provides a highly simplified illustration of this effect. In the illustration, gamma rays are depicted as bright lines radiating from a radioactive source. Since the lines are radiating outward, they are most highly concentrated in the vicinity of the source, thinning progressively as distance from the source increases. (In reality, gamma rays are invisible to humans.)

The inverse square law is an idealized calculation, based on several assumptions. The first assumption is that radiation is emitted from a "point source." For practical purposes, a small source of radiation can be considered a point source when we measure intensity at a distance of more than 10 times the source's largest dimension. For example, a source that is 1 cm wide and 2 cm high can be considered a point source if we

FIGURE 2

RADIATION INTENSITY DECLINES WITH DISTANCE FROM A SOURCE

The inverse square law is based on the observation that radiation becomes less intense the farther away one moves from the source. Depicted here is a highly simplified illustration of this effect. (In reality, gamma rays are invisible to humans.)



measure intensity at a distance greater than 20 cm (because the source's largest dimension is 2 cm, and 2 cm x 10 = 20 cm). Note that intensity falls off more slowly with distance from non-point sources such as large spills or pipelines with internal coatings of radioactive scale.

Several other assumptions must be considered when applying the inverse square law to an actual case. For example, it is assumed that radiation is emitted in the form of pure energy (e.g., gamma or X-rays). Furthermore, it is assumed that radiation is emitted uniformly in all directions, with no shielding or reflective surfaces to attenuate or amplify the intensity. With these assumptions in mind, the equation is as follows:

$$I_2 = I_1 \cdot \frac{(d_1)^2}{(d_2)^2}$$

where:

I_1 = intensity (or dose rate) no. 1; that is, the intensity of radiation at a reference distance (i.e., d_1) from a point source of radiation. Intensity may be stated in any customary unit for intensity or dose rate, such as roentgens or coulombs per kilogram.

I_2 = intensity (or dose rate) no. 2; that is, the intensity of radiation at a different distance (i.e., d_2) from a point source. We must state I_2 in the same unit as I_1.

d_1 = distance no. 1; that is, the reference distance from a point source that corresponds to I_1. Distance may be stated in any customary unit, such as meters or feet.

d_2 = distance no. 2; that is, the distance from a point source that corresponds to I_2. We must state d_2 in the same unit as d_1.

Calculating Radiation Intensity at a Distance

Once again, consider the incident illustrated in Figure 1. Measurements conducted during the postincident investigation demonstrated the intensity of the unshielded iridium-192 source was equal to 13.5 roentgens per hour (R/hr) at a distance of 100 cm (Holly & Beck, 1980). To better understand this measurement, consider that ionizing radiation produces ions while interacting with matter. Ions are molecules, atoms or subatomic particles having nonneutral (positive or negative) charges. Gamma rays produce ions by stripping electrical charges from atoms and molecules. The roentgen (R) is a measure based on the amount of ionization a radioactive source creates in air. Specifically, one roentgen is the amount of radiation required to produce one electrostatic unit of charge in one cubic centimeter of dry air. This means an intensity of 13.5 R/hr is sufficient to create 13.5 electrostatic units per hour in a cubic centimeter of air.

Intensity measurements are helpful because when combined with other details, they help us understand the potential for harm from radioactive sources. It is important to understand that intensity is not the same as dose equivalent. For example, the dose equivalents referenced in occupational exposure standards [e.g., sievert (Sv) or roentgen equivalent man (rem)] are calculated from absorbed doses [in grays (Gy) or radiation absorbed dose (rad)] modified by quality factors related to the vulnerability of the irradiated tissue.

In the Los Angeles incident illustrated in Figure 1, the technician received severe radiation burns after placing an unshielded radioactive source in his pocket for about 45 minutes. Other workers who briefly handled the source suffered less severe effects, including milder burns to the fingers, fatigue and extreme drowsiness, as well as chromosomal aberrations and other abnormal medical test results. These workers were in direct contact with the source, so the inverse square law has only limited application to their cases. We will apply our calculations instead to the cases of other workers who did not touch the source, but who were nonetheless present in the area at distances sufficient to consider the radioactive element as a point source.

Calculated example from the Los Angeles incident: Investigators of the Los Angeles incident reported the case of a worker who was present in the shop (Case 8, Ross et al., 1980). This coworker never touched the radioactive element, but he was located an average distance of about 76 cm from the source for a period of 20 to 30 minutes. Since we know the intensity was 13.5 R/hr at a distance of 100 cm, we can estimate the intensity of this worker's exposure using the inverse square law. The data for the problem can be summarized as follows:

- We are solving for the intensity of radiation at the worker's distance of 76 cm from the source. Intensity at this distance is currently unknown, so this intensity will be the value I_2 in the formula. The corresponding distance of 76 cm will then become the value of d_2.
- The intensity of the source was reported as 13.5 R/hr at a distance of 100 cm. This will be the reference intensity, so I_1 becomes 13.5 R/hr and the corresponding reference distance (d_1) will be 100 cm.

Based on these data, we will calculate the intensity of radiation (I_2) at the worker's distance in units of R/hr as follows:

Step 1: Start with the equation for the inverse square law:

$$I_2 = I_1 \cdot \frac{(d_1)^2}{(d_2)^2}$$

Step 2: Insert the known values for the reference intensity (I_1 = 13.5 R/hr), reference distance (d_1 = 100 cm), and the distance at which the worker was located (d_2 = 76 cm). Then solve for I_2 in R/hr:

$$I_2 = 13.5 \cdot \frac{100^2}{76^2} = 23.37\ R/hr$$

(rounded two places past the decimal)

Step 3: Our calculation indicates an expected intensity of about 23.37 R/hr at the worker's distance from the source of 76 cm. Since this worker's distance is closer than the reference distance, intensity is higher compared with the reference intensity of 13.5 R/hr.

Step 4: We can specify the worker's potential exposure further if we consider the amount of time he spent in the vicinity of the source. We initially calculated intensity in units of roentgens per hour. Let's now convert this intensity to roentgens per minute so we can determine the total potential exposure during the 20 to 30 minutes the worker was near the source.

Since there are 60 minutes per hour, we convert to roentgens per minute by dividing the hourly intensity by 60. In other words:

$$I_{2\ per\ minute} = I_{2\ per\ hour} \div 60$$

We calculated the intensity at 76 cm as 23.37 R/hr, so we insert this value for $I_{2\ \mathrm{per\ hour}}$, and solve for R/min as follows:

$$I_{2\ per\ minute} = 23.37 \div 60 = 0.39\ R/min$$

(rounded)

Our conversion indicates the intensity of radiation was about 0.39 R/min at the worker's distance of 76 cm. We now multiply this intensity by the actual minutes of exposure with the following equation:

$$I_{2\ total} = I_{2\ per\ minute} \cdot minutes\ of\ exposure$$

We determined that the intensity was 0.39 R/min at 76 cm and investigators reported the worker was located at this distance for 20 to 30 minutes. Inserting these values into the equation, we estimate the worker's total potential exposure was between 7.8 and 11.7 roentgens (depending on whether the actual duration was 20 or 30 minutes) as follows:

$$I_{2\ total\ (20\ minutes)} = 0.39 \cdot 20 = 7.8\ R$$

$$I_{2\ total\ (30\ minutes)} = 0.39 \cdot 30 = 11.7\ R$$

The worker in this case did not experience any symptoms; however, medical tests found evidence of chromosomal abnormalities that are commonly caused by ionizing radiation (i.e., chromosome breaks and dicentrics). We will not relate the worker's potential exposure to established exposure limits because this would require additional information and calculations that are beyond the scope of this article. Interested readers may consult standard health physics texts for calculations that convert exposures to dose equivalents.

Alternate example: For additional practice, consider a purely hypothetical case: Imagine that a radioactive source consisting of cobalt-60 is used to sterilize medical devices in an irradiation room. The radioactive source is normally shielded to protect workers who may enter the room for maintenance and other duties. During sterilization, workers leave the room, and the shielding is then retracted, exposing the radioactive source to irradiate the medical devices. The walls of the irradiation room are designed to contain harmful energy while the source is exposed inside.

International Atomic Energy Agency (IAEA, 2020) has reported cases in which workers were seriously injured or killed upon mistakenly entering irradiation rooms while a source was unshielded. For the hypothetical case, imagine that an equipment malfunction causes an operator to believe the radioactive source is safely shielded within its container, when in fact it is actually exposed. Further imagine that the operator goes into the room and stands for 10 seconds at a distance of 180 cm from the exposed radioactive source. Finally, imagine the source is known to produce gamma rays with an intensity of 3,936,000 R/hr at a distance of 30 cm. Based on this information, we can estimate the intensity using the inverse square law. We can summarize the data as follows:

- We are solving for the intensity of radiation at the operator's distance of 180 cm from the source. Intensity at this distance is currently unknown, so it will be represented by the variable I_2 in the formula. The corresponding distance of 180 cm will then become the value of d_2.
- As stated in the hypothetical scenario, the known reference intensity (I_1) is 3,936,000 R/hr at a reference distance (d_1) of 30 cm.

We use the original equation to solve for I_2:

$$I_2 = I_1 \cdot \frac{(d_1)^2}{(d_2)^2}$$

Insert the known values for the reference intensity (I_1 = 3,936,000 R/hr), reference distance (d_1 = 30 cm) and the operator's distance (d_2 = 180 cm) from the source. Then solve for I_2 in R/hr:

$$I_2 = 3{,}936{,}000 \cdot \frac{30^2}{180^2} = 109{,}333.33\ R/hr$$

(rounded)

Our calculation indicates an intensity of about 109,333.33 R/hr at the operator's distance of 180 cm from the source. Although this is only about 1/36th the intensity at the reference distance of 30 cm, it still represents a potentially lethal exposure.

The scenario indicated that the operator was located near the source for 10 seconds, so convert intensity to roentgens per second. There are 3,600 seconds per hour (60 minutes per hour x 60 seconds per minute = 3,600 seconds per hour). Thus, roentgens per second is equal to the hourly intensity divided by 3,600 seconds:

$$I_{2\ per\ second} = I_{2\ per\ hour} \div 3{,}600$$

Insert the previously calculated intensity of 109,333.33 R/hr as the value of I_2 per hour to obtain the following answer:

$$I_{2\ per\ second} = 109{,}333.33 \div 3{,}600 = 30.37\ R/sec$$

(rounded)

To calculate the operator's total potential exposure, multiply the intensity in R/sec by the duration in seconds with the following equation:

$$I_{2\ total} = I_{2\ per\ second} \cdot seconds\ of\ exposure$$

Inserting the calculated intensity of 30.37 R/sec and the duration of 10 seconds, we conclude the operator's total potential exposure was 303.7 R:

$$I_{2\ total\ (10\ seconds)} = 30.37 \cdot 10 = 303.7\ R$$

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 49.

1. Investigators of the Los Angeles incident reported the case of another worker in the shop who never touched the misplaced radioactive source (Case 9, Ross et al., 1980). This worker was located an average distance of 762 cm from the unshielded source for a period of about 30 minutes. Although this worker experienced extreme anxiety, he exhibited no other effects that could be definitively linked to the exposure. Knowing the intensity was 13.5 R/hr at a distance of 100 cm, estimate the intensity of radiation at this worker's location using the inverse square law as follows:

a. What was the intensity in R/hr at this worker's distance of 762 cm from the unshielded radioactive source? Use the equation for the inverse square law, and solve for the value of I_2 in units of R/hr.

b. Keeping in mind that there are 60 minutes per hour, convert intensity from R/hr to R/min. Solve by dividing R/hr by 60, as in the first example. The result will be a very small number, so round the answer to three places to the right of the decimal.

c. Finally, calculate the total potential exposure in units of R keeping in mind that this coworker was located at the distance of 762 cm for a period of 30 minutes. Solve by multiplying the calculated intensity in R/min by the number of minutes of exposure (30 in this case). Again, the value of intensity in R/min is small, so round to three places to the right of the decimal.

2. Consider a hypothetical case in which an equipment malfunction exposes an irradiation room operator for a period of 45 seconds at a distance of 90 cm from an exposed radioactive source. In this case, imagine the source is known to produce gamma rays with an intensity 1,418,040 R/hr at a distance of 50 cm. Estimate the radiation intensity for the operator using the inverse square law as follows:

a. What is the intensity in R/hr at this operator's distance of 90 cm from the unshielded radioactive source? Use the equation for the inverse square law, and solve for the value of I_2 in units of R/hr.

b. Keeping in mind that there are 3,600 seconds per hour, convert the intensity for the operator from R/hr to R/sec. Solve by dividing the intensity in R/hr by 3,600, as in the second example.

c. Finally, calculate the total potential exposure in units of R, keeping in mind this operator was located at a distance of 90 cm for a period of 45 seconds. Solve by multiplying the calculated intensity in R/sec by the number of seconds of exposure (45 in this case).

Concluding Comments

With the inverse square law, we can calculate the intensity of radiation at any distance providing we already know the intensity at some reference distance. This makes the inverse square law useful for designing distance-based control methods and for estimating the potential exposure of workers who unintentionally approach an unshielded radioactive source. The inverse square law has limitations. For example, the equation is designed for point sources of radiation, so it may not provide accurate results in the immediate vicinity of large, diffuse sources. Finally, the equation is designed for situations in which radioactive energy is emitted uniformly in all directions, which means it will not provide accurate results for highly collimated beams of radiation or in environments where reflective or absorptive materials are present.

How Much Have I Learned?

Try these problems on your own. Answers are on p. 49.

3. Imagine that an unshielded point source produces radiation with an intensity of 270 R/hr at a distance of 15 cm. Further imagine that a worker is exposed to the unshielded point source for a period of 47 minutes at a distance of 225 cm. Answer the following:

a. What is the intensity in R/hr at the worker's distance of 225 cm from the unshielded radioactive source? Use the equation for the inverse square law, and solve for the value of I_2 in units of R/hr.

b. Keeping in mind that there are 60 minutes per hour, convert the intensity for this worker from R/hr to R/min. Solve by dividing the intensity in R/hr by 60.

c. Calculate the total potential exposure in units of R, keeping in mind this worker was located at a distance of 225 cm for a period of 47 minutes. Solve by multiplying the calculated intensity in R/min by the number of minutes of exposure (47 in this case).

4. The inverse square law demonstrates several rules of thumb regarding the effects of distance on exposure. One rule of thumb is that a doubling of distance can reduce the intensity by a factor of four. In other words, a doubling of distance creates an intensity that is one-fourth that of the reference intensity. Let's test this rule by imagining an unshielded point source that produces a radiation intensity of 0.2 R/hr at a distance of 70 cm. Further imagine that a worker is exposed to the unshielded point source at a distance of 140 cm (which is twice the reference distance). Answer the following:

a. What is the intensity in R/hr at the worker's distance of 140 cm from the unshielded radioactive source? Use the equation for the inverse square law, and solve for the value of I_2 in units of R/hr.

b. The worker's distance of 140 cm was twice the reference distance of 70 cm. Was the intensity at 140 cm equal to one-fourth of the reference intensity, as predicted by the rule of thumb? Solve by dividing intensity at the worker's distance by the reference intensity. If the division results in an answer of 0.25, then intensity at the worker's distance will in fact be one-fourth of the reference intensity.

5. Another rule of thumb stemming from the inverse square law is that a tenfold increase in distance can reduce intensity by a factor of 100. This means that at 10 times the reference distance, the intensity will be 1/100th the intensity of the reference intensity. Let's test this rule by imagining an unshielded point source that produces a radiation intensity of 4 R/hr at a distance of 80 cm. Further imagine that a worker is exposed to the unshielded point source at a distance of 800 cm (which is 10 times the reference distance). Answer the following:

a. What is the intensity in R/hr at the worker's distance of 800 cm from the unshielded radioactive source? Use the equation for the inverse square law, and solve for the value of I_2 in units of R/hr.

b. The worker's distance of 800 cm was 10 times the reference distance of 80 cm. Was intensity at the worker's distance equal to 1/100th of the reference intensity, as predicted by the rule of thumb? Solve by dividing intensity at the worker's distance by the reference intensity. If the division results in an answer of 0.01, then intensity for the worker will in fact be 1/100th of the reference intensity.

For Further Study

Learn more from the following source: *Radiation Protection Qualification Standard Reference Guide*, by National Nuclear Security Administration, U.S. Department of Energy, 2009, **https://bit.ly/3oPgFXk**. PSJ

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Why would I put myself in those compromising situations as a young worker? Because, in my mind, that is what it meant to be a "good employee," and the culture of my family and safety was something I provided to others as a lifeguard, not worried about for myself, right?

Now, I look back on those days as a high school and college worker with a profound feeling that I was lucky. Regardless of how invincible I felt, I now know that I was at risk and, frankly, neither the employer nor the employee knew any better. This is not an excuse but a reality that safety professionals should recognize as an opportunity. City pools, community centers, recreation facilities, churches and local theaters have supported me and my siblings through our formative years. Adding to the list, retail and fast-food establishments have likely supported the early careers of many readers or their families. In all of these cases, neither the employer/supervisor nor the employee has any desire for harm to occur. However, in many cases the supervisor and employee do not know any better. While we as professionals may have conversations regarding safe work behaviors with young people in our lives, the majority of young workers are not so fortunate and must depend on their employers to provide the training. Through observation and experience, this seems akin to hoping for bad things not to happen rather than actively preventing their occurrence. There has to be a better way.

As we send our children, neighbors and emerging community leaders to work, we must ensure that as a professional community they have access to the safety training, resources and knowledge they need to grow and develop without harm. Is it our job? Not necessarily. However, I would argue that we have a professional duty to serve where there is a demonstrated opportunity. With the vulnerability of this workforce due to their lack of teaching, lack of experience and hazards present, look for opportunities to educate and support where practicable. Even simple consultation, insight and support could make a significant impact on the immediate or lasting futures of these employees during an impressionable stage.

The opportunities will look different in each organization and to each professional, and, as always, one should only support where one is qualified and competent. With that said, imagine the impact if each ASSP chapter, let alone member, looked to engage one set of youth in their community. What would it look like if people were provided with awareness regarding workplace safety when they were young employees instead of when they return to the workforce to begin a full-time career? What about those who suffered some sort of incident? Imagine if our organization could impact those statistics for the better and allow for life-changing, not life-altering, development. The goal should be to teach young workers how to act safely in the workplace and instill them with a sense of awareness that will help them navigate the dynamic workplace hazards they face. They should be empowered to speak up for their safety, not to find fault in what are often already burdened workplaces. The objective of the safety professional should be to lend support and expertise where it might be accepted at workplaces throughout our communities that employ young workers. So, as we encounter young employees heading to work in our communities, take a moment to stop and see where the insight of a safety professional might be valuable and let us work as an association of community leaders to ensure the betterment of our neighborhoods and the young workers growing within them. **PSJ**

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Math Toolbox, continued from pp. 44-47

Answers: The Case of the Misplaced Radioactive Element

You Do the Math

Your answers may vary slightly due to rounding.

1.a. $I_2 = 13.5 \cdot \frac{100^2}{762^2} = 0.23\ R/hr$ (rounded)

1.b. $I_{2\ per\ minute} = 0.23 \div 60 = 0.004\ R/min$ (rounded)

1.c. 30 minutes · 0.004 R/min = 0.12 R

2.a. $I_2 = 1{,}418{,}040 \cdot \frac{50^2}{90^2} = 437{,}666.67\ R/hr$ (rounded)

2.b. $I_{2\ per\ second} = 437{,}666.67 \div 3{,}600 = 121.57\ R/sec$ (rounded)

2.c. 45 seconds x 121.57 R/sec = 5,470.65 R

How Much Have I Learned?

3.a. $I_2 = 270 \cdot \frac{15^2}{225^2} = 1.2\ R/hr$

3.b. $I_{2\ per\ minute} = 1.2 \div 60 = 0.02\ R/min$

3.c. 47 minutes x 0.02 R/min = 0.94 R

4.a. $I_2 = 0.2 \cdot \frac{70^2}{140^2} = 0.05\ R/hr$

4.b. Yes, intensity at the worker's distance is one-fourth of the reference intensity (0.05 ÷ 0.2 = 0.25).

5.a. $I_2 = 4 \cdot \frac{80^2}{800^2} = 0.04\ R/hr$

5.b. Yes, intensity at the worker's distance is one-tenth of the reference intensity (0.04 ÷ 4 = 0.01).