pXRF Safety

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Introduction

When X-ray radiation from the **handheld XRF** (**pXRF**) excites atoms in the sample, the atoms release fluorescent X-rays. The energy level of each fluorescent X-ray create is characteristic of the element excited; as a result, one can tell what elements are present. The **Olympus Delta pXRF** detects and determines the fluorescent X-ray energies produced. As the pXRF emits radiation (from 8-40keV), a comprehensive knowledge of radiation safety and procedures is needed.

Radiation Safety

What is Radiation?

The term radiation is used with all forms of energy: light, X-rays, radar, gamma rays, microwaves, and more. For the purpose of this manual, radiation refers to invisible waves or particles of energy emitted from a radioactive source or X-ray tube. Radiation if received in too large a quantity, can have an adverse health effect on humans. There are two distinct types of radiation: non-ionizing and ionizing.

Non-ionizing Radiation

Non-ionizing radiation does not have the energy necessary to ionize an atom (i.e., to remove electrons from neutral atoms). Sources of non-ionizing radiation include light, microwaves, power lines, and radar. Although this type of radiation can cause biological damage, such as a sunburn, it is generally considered less hazardous than ionizing radiation.

Ionizing Radiation

Ionizing radiation has enough energy to remove electrons from neutral atoms. Ionizing radiation is of concern due to its potential to alter the chemical structure of living cells. These changes can alter or impair the normal functions of a cell. Sufficient amounts of ionizing radiation can cause hair loss, blood changes, and varying degrees of illness.
There are four basic types of ionizing radiation, emitted from different parts of the atom (see *Figure 1*, below):

- Alpha particles
- Beta particles
- Gamma rays and X-rays
- Neutron Particles

The penetrating power for each of the four basic radiations varies significantly.

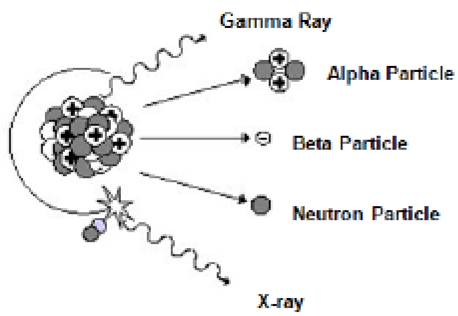

Figure 1. Types of Ionizing Radiation and Their Sources

Radioactivity-Emitting Materials

Some materials are inherently radioactive, such as the 1 micro-Curie ^{60}Co sources used to calibrate the natural gamma radiation multisensor logger (NGRL) in the Physical Properties laboratory. Not only do they emit radiation (which can be ionizing or non-ionizing, and present direct hazards), but they could also theoretically be ingested, injected, or inhaled.
Alpha and beta particles have little ability to penetrate the skin, so alpha- and beta-radiation sources are most dangerous when they are taken into the body; this is called **radiation poisoning**. X-ray, gamma ray, and neutron sources are able to penetrate the skin, so the risk is both direct (**radiation burn** or **acute radiation exposure**) and indirect (**radiation poisoning**).

Radiation Producing Devices

In the case of the pXRF, the X-rays are generated by a cathode-ray tube. If current is applied to the tube in sufficient voltage (>8 kV) to generate X-rays, radiation is produced. If no current is flowing, no radiation is produced. Therefore, the pXRF is completely safe from a radiation standpoint when it is unpowered.
Note: the pXRF emits only X-rays. For this reason, this manual will preferentially focus on x-rays from this point on.

X-Rays

- Electromagnetic waves or photons of pure energy that have no mass or electrical charge
- X-rays are emitted from the inner electron shells of atoms, or from an RPD
- Ionize atoms by interacting with electrons

Distance

Because X-rays (and gamma rays) have no charge or mass, they are highly penetrating and can travel quite far. Range in air can easily reach several hundred feet. *Figure 2* reflects this graphically.

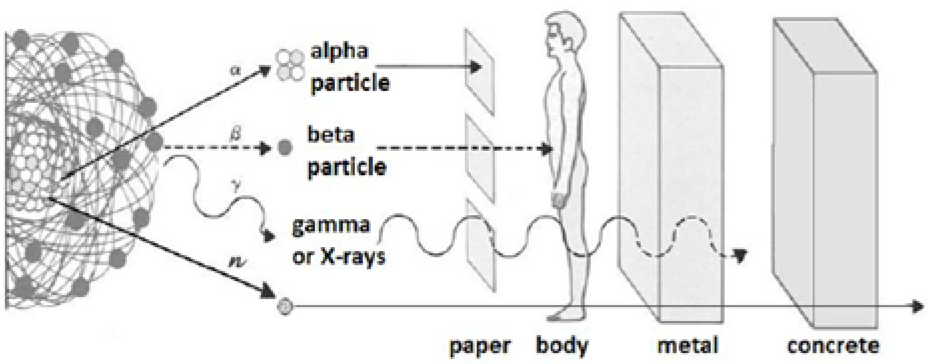

Figure 2. Penetrating Power of Radiation

Shielding

X-rays interact with matter and lose energy because of that interaction. Therefore, the best shielding materials are dense, such as concrete, steel, or lead.

Hazard

Due to their range and penetrating ability, X-ray radiation primarily is considered an external hazard: i.e. they're hazardous through the skin.

Biological Effects of Radiation

Cell Sensitivity

The human body is composed of over 50,000 billion living cells. Groups of these cells make up tissues, which in turn make up the body's organs. Some cells are more resistant to viruses, poisons, and physical damage than others. The most sensitive cells are those that are rapidly dividing. Radiation damage may depend on both resistance and level of activity during exposure.

Acute and Chronic Doses of Radiation

All radiation, if received in sufficient quantities, can damage living tissue. The key lies in how much and how quickly a radiation dose is received. Doses of radiation fall into one of two categories: acute or chronic.

Acute Dose

An acute dose is a large dose of radiation received in a short period of time that results in physical reactions due to massive cell damage (acute effects). The body can't replace or repair cells fast enough to undo the damage right away, so the individual may remain ill for a long period of time. Acute doses of radiation can result in reduced blood count and hair loss.

Recorded whole body doses of 10,000-25,000 mrem have resulted only in slight blood changes with no other apparent effects. Radiation sickness occurs at acute doses greater than 100,000 mrem. Recovery from an acute dose to the whole body may require a number of months. Whole body doses of 500,000 mrem or more may result in damage too great for the body to recover from. Only extreme cases (e.g., a Chernobyl-scale nuclear accident) result in doses so high that recovery is unlikely.

Note: Acute dose to a part of the body most commonly occurs in industry (use of X-ray machines), and often involve exposure of extremities (e.g., hand, fingers). Sufficient radiation doses may result in loss of the exposed body part. The prevention of acute doses to part of the body is one of the most important reasons for proper training of personnel.

Chronic Dose

A chronic dose is a small amount of radiation received continually over a long period of time, such as the dose of radiation we receive from natural background sources every day.

Chronic Dose vs. Acute

The body tolerates chronic doses of radiation better than acute doses because:

- Only a small number of cells need repair at any one time.
- The body has more time to replace dead or non-working cells with new ones.
- Radical physical changes do not occur as with acute doses.

Biological Damage Factors

Biological damage factors are those factors, which directly determine how much damage living tissue receives from radiation exposure, and include:

- **Total dose**: the larger the dose, the greater the biological effects.
- **Dose rate**: the faster the dose is received, the less time for the cell to repair.
- **Type of radiation**: the more energy deposited the greater the effect.
- **Area exposed**: the more body is exposed, the greater the biological effects.
- **Cell sensitivity**: rapidly dividing cells are the most vulnerable.

Putting Risks in Perspective

Acceptance of any risk is a very personal matter and requires that a person make informed judgments, weighing benefits against potential hazards.

Risk Comparison

The following summarizes the risks of radiation exposure:

- The risks of low levels of radiation exposure are still unknown.
- Since ionizing radiation can damage chromosomes of a cell, incomplete repair may result in the development of cancerous cells.
- There have been no observed increases of cancer among individuals exposed to occupational levels of ionizing radiation.

Using other occupational risks and hazards as guidelines, nearly all scientific studies have concluded the risks of occupational radiation doses are acceptable by comparison. By learning to respect and work safely around radiation, we can limit our exposure and continue to enjoy the benefits it provides.

Table 1a and *1b*., below summarize the risks associated with various activities; note the low loss associated with occupational radiation exposure (when proper controls are in place).

Average Estimated Days Lost By Industrial Occupations	
Occupation*	**Estimated Days Lost**
Mining/Quarrying	328
Construction	302
Agriculture	277
Transportation/Utilities	164
Radiation dose of 5 rem per yr for 30 years	150
All industry	74
Government	55
Service	47
Manufacturing	43
Trade	30

Average Lifetime Estimated Days Lost Due to Daily Activities	
Activity*	**Estimated Days Lost**
Cigarette smoking	2250
25% Overweight	1100
Accidents (all types)	435
Alcohol consumption (U.S. avg.)	365
Driving a motor vehicle	207
Medical X-rays (U.S. avg.)	6
1 rem Occupational Exposure	1
1 rem per year for 30 years	30

***Note:** based on US data only*

Table 1a (left) and 1b (right). Average estimated days lost by occupation and daily activities.

Radiation Dose Limits

To minimize the risks from the potential biological effects of radiation, the state health departments and the Nuclear Regulatory Commission (NRC) have established radiation dose limits for occupational workers as shown in *Table 2a* and *2b*, below.. The limits apply to those working under the provisions of a specific license or registration.

Typical Radiation Doses from Selected Sources (Annual)	
Exposure Source	**mrem per year**
Radon in homes	200
Medical exposures	53
Terrestrial radiation	30
Cosmic radiation	30
Round trip US by air	5
Building materials	3.6
Worldwide fallout	<1
Natural gas range	0.2
Smoke detectors	0.0001

Average Occupational Doses	
Occupation	**Exposure (mrem per year)**
Airline flight crewmember	1000
Nuclear power plant worker	700
Grand central station worker	120
Medical personnel	70
DOE/DOE contractors	44

Table 2a (left) and 2b (right). Typical radiation doses from selected sources and average occupational doses.

In general, the larger the area of the body that is exposed, the greater the biological effects for a given dose. Extremities are less sensitive than internal organs because they do not contain critical organs. That is why the annual dose limit for extremities is higher than for a whole body exposure that irradiates the internal organs. *Table 3* lists the exposure limits for different regions of the body.

Type of Body Area	Description	Allowable Limit (rem /year)

Whole Body	The whole body is measured from the top of the head to just below the elbow and just below the knee. The limit is the sum of both internal and external exposure	5
Extremities	The hands, arms below the elbows, the feet, and legs below the knees	50
Skin	The entirety of the skin	50
Organs or Tissues	All organs and tissues, including the brain	50
Lens of the Eye	The cornea (the internal eye and retina are included in organs or tissues)	15
Declared Pregnant Worker	**If a worker declares their pregnancy (formally and in writing), their radiation exposure limits are reduced by a factor of 100; the exposure limit for the embryo/fetus is as shown**	**0.5 (entire gestation period)**

Table 3: Dose Limits by Body Area

Additional Note: Pregnancy

The JRSO does not permit pregnant women to sail on the *R/V JOIDES Resolution*. The environmental controls and list of hazardous materials, including radioactive materials and radiation-producing devices, on board the ship are not designed with pregnant women in mind. If a woman determines that she is, or has become, pregnant, inform the ship's doctor immediately to prevent potential harm to the embryo/fetus.

Measuring Radiation

Since we cannot detect radiation through our senses, some regulating agencies require special devices for personnel operating an XRF in order to monitor and record the operator's exposure. These devices are commonly referred to as dosimeters, and the use of them for monitoring is called dosimetry.

- Wear an appropriate dosimeter that can record low energy photon radiation
- Dosimeters with a wear period of three months may be used
- Each dosimeter will be assigned to a particular person and is not to be used by anyone else

Measuring Devices

Several devices are employed for measurement of radiation doses, including ionization chambers, Geiger-Mueller tubes ("Geiger counter"), pocket dosimeters, thermoluminescence devices (TLD's), optically stimulated luminescence dosimeters (OSL) and film badges. On the ship, the JRSO has Geiger counters and film badges.

The Geiger-Mueller Tube

The Geiger-Mueller (GM) Tube is very similar to the ion chamber, but is much more sensitive. The voltage of its static charge is so high that even a very small number of ion pairs will cause it to discharge. A GM tube can detect and measure very small amounts of beta or gamma radiation.

Dosimeters

These are two common types of dosimeters: whole body and extremity

Whole Body Dosimeters:

A whole body dosimeter is used to measure both shallow and deep penetrating radiation doses. It is normally worn between the neck and waist.

Finger Ring:

A finger ring a film dosimeter in the shape of a ring, which is worn by workers to measure the radiation exposure to the extremities. Finger rings are the appropriate tool for pXRF use, since the hands are the most likely body part to be in proximity to the X-ray source.

Reducing Exposure

ALARA

Natural and man-made background radiation is ubiquitous, providing an average annual radiation dose of 0.360 rem to every U.S. citizen. Large fluctuations in background radiation, by geographical location, have not been shown to result in any measurable increase in risk of any health effect. Nevertheless, any radiation dose received occupationally would be in excess of the background radiation dose received and can therefore be assumed to carry with it additive risk of deleterious effect.
State and federal regulations therefore establish a system of dose **limitation** and **minimization**. Individual doses are **limited** to ensure that deterministic effects (such as cataracts) are avoided and that total lifetime risks of stochastic effects (such as cancer and hereditary effects) do not exceed overall health risks for those persons working in safe industries. However, regulations also require that licensees further **minimize** radiation doses to individuals and to groups of individuals to the extent practical, social, economic and technological factors taken into account.
This concept or philosophy is given the special name **ALARA** which is an acronym for **As Low As is Reasonably Achievable**. That is the safety standard for working with all types of radioactive sources and radiation-producing devices, and it means that exposure should be as low as possible, within a reasonable limit.
While dose limits and administrative control levels already help ensure very low radiation doses, it is possible to reduce these exposures even more. The main goal is to reduce ionizing radiation doses to a level that is **ALARA**. There are three basic practices to maintain external radiation:

- Time
- Distance
- Shielding

Time

The first method of reducing exposure is to limit the amount of time spent in a radioactive area: the shorter the time of exposure, the lower the amount of exposure.
The effect of time on radiation could be stated as:
Dose = Dose Rate X Time
This means the less time you are exposed to ionizing radiation, the smaller the dose you will receive, directly proportional to the time of exposure. Half the time means half the dose, and vice versa.

Distance

The second method for reducing exposure is by maintaining the maximum possible distance from the radiation source to the operator or member of the public. The principle of distance is that the exposure rate is reduced as the distance from the source is increased; as distance is increased, the amount of radiation received is reduced.
This method can best be expressed by the **Inverse Square Law**, graphically represented below in *Figure 3*. The inverse square law states that doubling the distance from a point source reduces the dose rate (intensity) to ¼ of the original. Tripling the distance reduces the dose rate to 1/9 of its original value.

$$C \times (D_1)^2 / (D_2)^2 = I$$

C = the intensity (dose rate) of the radiation source
D_1 = the distance at which C was measured
D_2 = the actual distance from the source
I = the new level of intensity at distance D_2 from the source

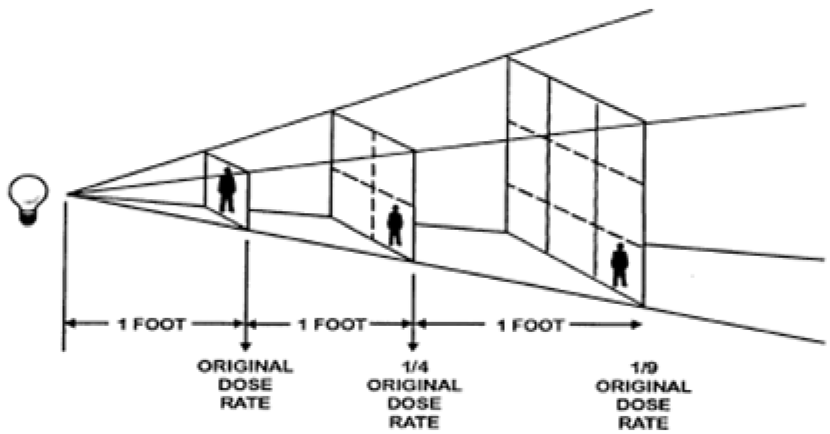

Figure 3. Graphical Representation of the Inverse Square Law

The inverse square law does not apply to sources of greater than a 10:1 ratio (distance: source size), or to the radiation fields produced from multiple sources.

Shielding

The third (and most important) method of reducing exposure is shielding. Shielding is generally considered to be the **most effective method of reducing radiation exposure** and consists of using a material to absorb or scatter the radiation emitted from a source before it reaches an individual. Different materials are more effective against certain types of radiation than others. The shielding ability of a material also depends on its density, or the weight of a material per unit of volume.
Although shielding may provide the best protection from radiation exposure, there are still several precautions to keep in mind when using the Olympus Delta Handheld XRF:

- Persons outside the shadow cast by the shield are not necessarily 100% protected.

Note: All persons not directly involved in operating the XRF should be kept at least three feet away.

- A wall or partition may not be a safe shield for persons on the other side.

Note: The operator should make sure that there is no one on the other side of the wall.

- Scattered radiation may bounce around corners and reach an individual, whether directly in line with the test location or not.

Specific pXRF User Requirements

Radiation from the pXRF

The user and anyone working in the area of the pXRF should always take reasonable precautions when using and working around the device. That means keeping body parts out of and away from the nose of the instrument (where the source is) and keeping a distance between the active source and themselves if not working directly with the instrument.

Radiation Scatter

Radiation scatter is produced whenever an absorbing material is directly irradiated from a nearby source. The spectrum displays the scatter from the main excitation source (X-ray tube) as well as the radiation produced through the pXRF process. This spectrum represents the X-rays that reach the detector. X-rays produced through fluorescence are randomly distributed in all directions. Scattering, however, is not uniform and is dependent on the sample being tested, the energy of the radiation, and other factors.

The X-ray tube within the pXRF is used to irradiate a chosen material at very close range with a narrow, collimated beam. The X-rays from the tube excite the atoms of the material, which then produce K- or L-shell X-rays. These fluorescent X-rays, the main beam, and scattered radiation can be contained inside the instrument if the sample is sufficiently dense and thick. For example: according to the manufacturer, a U.S. quarter can effectively contain the radiation inside the instrument; a plastic lid, in comparison, cannot. The main beam is much stronger than the fluorescence or scattered radiation and should be avoided.

Backscatter

The pXRF analyzer generates spectrum data by analyzing the specific X-ray energies that get back to the detector. Because the X-rays travel in all directions, it is possible for an X-ray to miss the detector and be scattered in the direction of the operator. This is referred to as backscatter.

Although the XRF is specifically designed to limit backscatter reaching the operator, there is always the possibility that a small number of X-rays may scatter beyond the detector. In the case of light or thin samples that do not contain the main beam, the main beam may then be scattered back towards the operator. In this case, a shield around the sample should be used.

Important! Discrete samples, including powders mounted in plastic cups, should only be analyzed in the Olympus pXRF **Test Stand**. The walls of the Test Stand are lead-lined. When the pXRF is secured in the Test Stand and the lid is closed, the radiation emission is considered negligible.

To ensure safe operation of the system, it is vital that the operator understand the radiation field. The Radiation profile contains measurements of the radiation field. **The profile should be studied carefully by anyone that operates the handheld XRF, in order to better understand and apply the practices of ALARA doses (using time, distance and shielding)**.

Radiation Profile

Figure 4, below, states the Olympus DELTA Series pXRF measured doses of scattered radiation, based on pXRF target and position.

Model: DELTA Series							Date: Oct. 2012 and Jan. 2013		
Survey instrument		Ludlum Model 3 44-7 probe		Ludlum Model 2241 44-172 probe		Performed by: F. Cook R. Nasella	Validated by: M. L. Tremblay		
Probe head: Aluminum									
Measured dose rate in μSv/h[c] — Secondary radiation (scatter)									
Mode(s)	**Substrate**	**Voltage (kV)**	**Amperage (μA)**	**Filter**	**Trigger — T**	**Close — F**	**5 cm — F1**	**10 cm—F2**	**30 cm (calculated)**
Alloy Plus, Mining, Mining Plus, GeoChem 1, 3-Beam Soil 2, HalFree 1, RoHS 1 (plastic)	316 stainless	40	100	Aluminum	BK[d]	7	6	BK	BK
	Al (319 AA)				7	300	120	30	4
	EC 680K				45	900	500	320	19
	Soil (SiO_2)				20	400	250	70	9
RoHS 1, 4-Beam RoHS 1 (plastic), RoHS 2, 4-Beam RoHS 2 (alloy)	PVC-Blank	50[e]	80	Copper	10	840	400	250	15
	EC 680K				16	1800	800	500	30
	71X SR2 (solder)				BK	5	1	BK	BK
Alloy, Mining	316 stainless	35	100	Aluminum	BK	2	2	BK	BK
	Soil (SiO_2)				5	130	60	20	
Alloy Plus 3	316 stainless	8	200	Open	BK	BK	BK	BK	BK
	Al (319 AA)				BK	BK	BK	BK	BK
Alloy Plus 2	316 stainless	13	200	Open	BK	BK	BK	BK	BK
	Al (319 AA)				BK	BK	BK	BK	BK
Alloy 2	316 stainless	15	200	Iron	BK	BK	BK	BK	BK
	Al (319 AA)				BK	BK	BK	BK	BK
3-Beam Soil 1, Mining Plus	Soil (SiO_2)	50[e]	80	Copper	25	1500	800	450	30
3-Beam Soil 1	Soil (SiO_2)	40	100	Copper	10	400	220	70	8
RoHS 2 (alloy)	PVC-Blank	40	100	Copper	5	200	90	30	3
	EC 680K				4	700	420	300	16
Geochem 2, Mining Plus 2	Soil (SiO_2)	10	200	Open	BK	BK	BK	BK	BK
3-Beam Soil 3	Soil (SiO_2)	15	200	Thin aluminum	BK	BK	BK	BK	BK
Lead 2	71X SR2 (solder)	18	200	Aluminum	BK	BK	BK	BK	BK
Lead 1	71X SR2 (solder)	25	100	Aluminum	BK	BK	BK	BK	BK
HalFree 2	EC 680K	10	200	Open	BK	8	1	BK	BK
HalFree 2	EC 680K	12	200	Open	BK	70	13	4	BK

a. Table revision D, January 2013.
b. Aluminum probe head only, no probe shield in place.
c. To convert measurements to mR/h, divide results by 10.
d. BK = Background reading (< 1 μSv/h).
e. All 50 kV readings are taken with standard probe shield in place.

Figure 4. Olympus DELTA Series Measured Doses Chart

Handheld XRF Analyzer Safety Design

To control X-ray emissions, and thereby minimize the possibility of accidental exposure, the Olympus pXRF analyzer has a standard **safety interlock structure** consisting of two features listed below. Be sure to understand the **software trigger lock** setting to understand whether the trigger is "armed" or not.

Software proximity sensor

Within two seconds of starting a test, the analyzer detects if a sample is in front of the measurement window. If no sample is detected, the test aborts to prevent accidental exposure. Upon an abort action, the filter wheel returns to the 0 position, the X-rays shut off (the tube current decreases to 0.0 µA), and the red light stops blinking. If the probe is pulled away from the sample while a test is in progress, testing will stop and X-rays will shut off.

Software trigger lock

After a five-minute lapse between tests (default time), the trigger automatically locks. The pXRF analyzer also has a dead man trigger protocol, in which the user is required to pull and hold the trigger for the duration of the test. Releasing the trigger prematurely will abort the test.

Indicators and Alarms

X-ray Indicator

An X-ray indicator alerts the operator when the tube is receiving power and when X-rays are emitted from the analyzer through the measurement window. The X-ray indicator is located on the upper rear portion of the analyzer. This indicator consists of a six-element red LED array, and has three states:

X-ray indicator OFF

This signifies that the X-ray tube is disabled, and that there is no possibility of radiation exposure to you or bystanders. The instrument can be carried or set down safety in this condition.

X-ray indicator continuously ON

Solid red LED array. This signifies that the X-ray tube is enabled, and that there is no radiation exposure to you or bystanders. The instrument can be carried or set down safety in this condition.

X-ray indicator flashing ON

Blinking red LED array. This signifies that the X-ray tube is powered on and that the analyzer is emitting X-ray radiation through the measurement window. In this condition, the analyzer must be pointed toward a test sample and never at a human being.

Audible Alarm Protocol

As a warning, the audible signal emits three tones when the X-ray tube is about to emit X-rays. During the subsequent testing period, the audible alarm maintains a "chirping" signal throughout the duration of the test. This feature is mandatory.

Infra-Red Sensor

The pXRF has an **infrared sensor** that detects the presence of an object in front of the pXRF source. If no object is detected, the pXRF will not activate the source.

Radiation Safety Tips for Using the XRF

All operators should follow minimum safety requirements discussed below. When handled properly, the amount of radiation exposure received from the pXRF will be negligible. However, the following safety tips are provided to help ensure safe and responsible use:

1. **WARNING**: No one but the operator should be allowed to be closer than 3 feet from the pXRF, particularly the beam port. Ignoring this warning could result in unnecessary exposure.
2. **WARNING**: The operator should never defeat the IR sensor in order to bypass this part of the safety circuit. Defeating this safety feature could result in over-exposure of the operator.
3. Do not allow anyone other than trained personnel to operate the pXRF
4. Be aware of the direction that the X-rays travel when the red light is on and avoid placing any part of your body (e.g., eyes, hands) near the X-ray port to stabilize the instrument during operation.
5. Never hold a sample up to the X-ray port for analysis by hand; hold the instrument to the sample.
6. Establish a no-access zone at a sufficient distance from the instruments measurement window, which will allow air to attenuate the beam.
7. Enclose the beam working area with protective panels (e.g., >3.0 mm stainless steel).
8. Wear an appropriate dosimeter (see the Laboratory Officer for more information on when a dosimeter is called for).
9. The operator is responsible for the security of the handheld XRF. When in use, the device should be in the operator's possession at all times (i.e., either in direct sight or a secure area).

10. Always store the instrument in a secure location when not in use.
11. During transport to and from the set up location, store the instrument in a cool, dry location.
12. **WARNING**: Pregnant women should not use the pXRF or work in proximity to it. See **Additional Note, Pregnancy**, above, for more information. Radiation exposure can be harmful to an embryo or developing fetus!

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