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# X-Ray Radiation Safety

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*Manual for Operator Training*

*Bruker Elemental Hand-held XRF Analyzers*



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## 1. What is Radiation?

The term radiation is used with all forms of energy—light, X-rays, radar, microwaves, and more. For the purpose of this manual, however, radiation refers to invisible waves or particles of energy from radioactive sources or X-ray tubes. High levels of radiation may pose a danger to living tissue because it has the potential to damage and/or alter the chemical structure of cells. This could result in various levels of illness (mild to severe).

The user of a Bruker XRF analyzer should understand the nature of radiation and how to be safe using XRF analyzers.

## 2. Radiation Terminology

Before examining the subject of radiation in more detail, there are several important terms to be reviewed and understood.

**Bremsstrahlung**: The X-rays or “braking” radiation produced by the deceleration of electrons, namely in an X-ray tube.

**Characteristic X-rays**: X-rays emitted from electrons during electron shell transfers.

**Fail-Safe Design**: One in which all failures of indicator or safety components that can reasonably be anticipated cause the equipment to fail in a mode such that personnel are safe from exposure to radiation. For example, if the red lamp indicating “X-RAY ON” fails, the production of X-rays would be prevented.

**Ion**: An atom that has lost or gained an electron.

**Ion Pair**: A free electron and positively charged atom.

**Ionization**: The process of removing electrons from the shells of neutral atoms.

**Ionizing Radiation**: Radiation that has enough energy to remove electrons from neutral atoms.

**Isotope**: Atoms of the same element that have a different number of neutrons in the nucleus.

**Non-ionizing Radiation**: Radiation that does not have enough energy to remove electrons from neutral atoms.

**Normal Operation**: Operation under conditions suitable for collecting data as recommended by manufacturer, including shielding and barriers.

**Primary Beam**: Ionizing radiation from an X-ray tube that is directed through an aperture in the radiation source housing for use in conducting X-ray fluorescence measurements.

**Radiation**: The energy in transit in form of electromagnetic waves or particles.

**Radiation Generating Machine**: A device that generates X-rays by accelerating electrons, which strike an anode.

**Radiation Source**: An X-ray tube or radioactive isotope.

**Radiation Source Housing:** That portion of an X-ray fluorescence (XRF) system, which contains the X-ray tube or radioactive isotope.

**Radioactive Material:** Any material or substance that has unstable atoms, which are emitting radiation.

**System Barrier:** That portion of an area, which clearly defines the transition from a controlled area to a radiation area and provides the necessary shielding to limit the dose rate in the controlled area during normal operation.

**X-ray Generator:** That portion of an X-ray system that provides the accelerating voltage and current for the X-ray tube.

**X-ray System:** Apparatus for generating and using ionizing radiation, including all X-ray accessory apparatus, such as accelerating voltage and current for the X-ray tube and any needed shielding.

### 3. Types of Radiation

As stated earlier, radiation consists of invisible waves or particles of energy that could have a health effect on humans if received in too large a quantity. There are two distinct types of radiation: *non-ionizing* and *ionizing*.

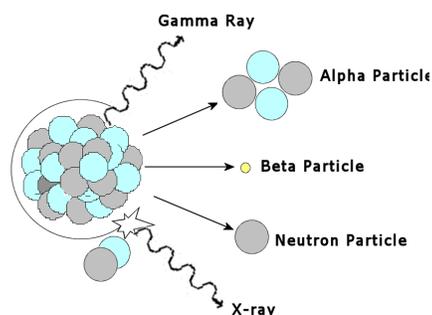
#### 3.1. Non-ionizing Radiation

Non-ionizing radiation does not have the energy needed 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, like sunburn, it is generally considered less hazardous than ionizing radiation.

#### 3.2. Ionizing Radiation

Ionizing radiation does have 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. These levels are approximately 1,000 times higher than levels that the public or workers are permitted to receive.

The four basic types of ionizing radiation are emitted from different parts of an atom, as shown in the image to the right.



**NOTE:** Bruker handheld XRF devices only emit X-rays.

**Alpha Particles** have a large mass, consisting of two protons and two neutrons, and a positive charge. They ionize by stripping away electrons (-) from other atoms with its positive (+) charge, and are generally only considered a radiation hazard if ingested or inhaled.

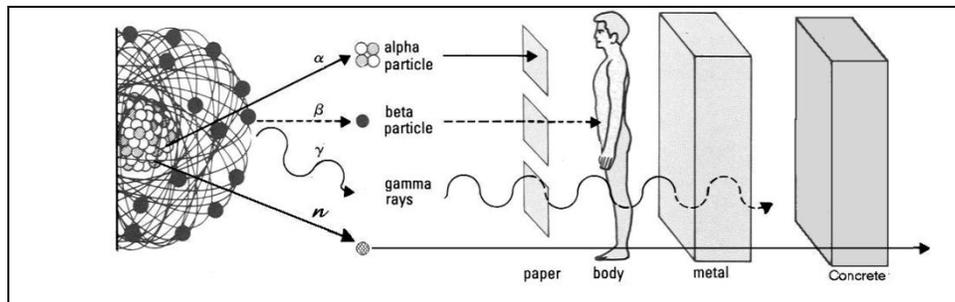
**Beta Particles** are high-energy, high-speed electrons or positrons which form ionizing radiation also known as beta rays. They ionize other atoms by stripping electrons out of their orbits with their negative charge, and are primarily a radiation hazard only to the skin and eyes.

**Gamma Rays and X-rays** are electromagnetic waves or photons of pure energy that have no mass or electrical charge. They ionize atoms by interacting with electrons, and are best shielded by use of dense materials, such as concrete, lead, or steel. Bruker handheld devices produce X-rays.

**Neutron Particles** are ejected from the nucleus of an atom during the normal operation of a nuclear reactor or particle accelerator, as well as the natural decay process of some radioactive elements. They can split atoms by colliding with their nuclei, forming two or more unstable atoms and cause ionization as they try to become stable. They are best shielded by materials with a high hydrogen content (water, concrete or plastic).

### 3.3. Penetration

The penetrating power for each of the four basic radiations varies significantly, as shown below.



## 4. Units for Measuring Radiation

The absorption of radiation into the body, or anything else, depends upon two things: the type of radiation involved and the amount of radiation energy received. Internationally, the units for measuring radiation are the *Gray* and *Sievert*; in the USA, the units are the *rad* and *rem*.

### 4.1. Rad (Radiation Absorbed Dose)

A rad is:

- A unit for measuring the amount of radiation energy absorbed by a material (i.e., dose)
- Defined for any material (e.g., 100 ergs/gm)
- Applied to all types of radiation
- Not related to biological effects of radiation in the body
- 1 rad = 1000 millirad (mrad)
  - The Gray (Gy) is the System International (SI) unit for absorbed energy
  - 1 rad = 0.01 Gray (Gy) and 1 Gray = 100 rad



### 4.2. Rem

Actual biological damage depends upon the concentration as well as the amount of radiation energy deposited in the body. The rem is used to quantify overall doses of radiation, their ability to cause damage, and their dose equivalence (see below).

A rem is:

- Is a unit for measuring dose equivalence
- Is the most commonly used unit of radiation exposure measure
- A term that pertains directly to humans
- Takes into account the energy absorbed (dose); the quality of radiation; the biological effect of different types of radiation in the body and any other factor. For gamma and X-ray radiation all of these factors are unity so that for these purposes a rad and a rem are equal.
- 1 rem = 1000 millirem (mrem)
  - Sievert is the SI unit for dose equivalence
  - 1 rem = 0.01 Sievert (Sv) and 1Sv = 100 rem

### 4.3. Dose and Dose Rate

*Dose* is the amount of radiation you receive during any exposure.

*Dose Rate* is the rate at which you receive the dose.

**Example:**  
 $Dose\ rate = dose/time = mrem/hr$   
 $Dose = dose\ rate \times time = mrem$

## 5. Significant Doses

| 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        |

*\* Based on U.S. data only*

| 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                       |

As stated previously, the general public is exposed daily to small amounts of radiation. However, there are four major groups of people that have been exposed in the past to significant levels of radiation. Because of this we know much about ionizing radiation and its biological effects on the body. The

earliest radiation workers, such as radiologists, received large doses of radiation before biological effects were recognized. Since then, safety standards have been developed to protect such employees.

The more than 100,000 people who survived the atomic bombs dropped on Hiroshima and Nagasaki, those involved in accidents like Chernobyl, and those who have received radiation therapy for cancer are examples of large groups that have received significant doses of radiation.

## 6. Biological Effects of Radiation

### 6.1. Cell Sensitivity

The human body is composed of billions of 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. Rapidly dividing cells are the most sensitive cells, which is why exposure to a fetus is so carefully controlled. Radiation damage may depend on both resistance and level of activity during exposure.

### 6.2. 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 100 – 250 mSv (10 - 25 rem) have resulted only in slight blood changes with no other apparent effects.

#### **Radiation Sickness**

Radiation sickness may occur at acute doses greater than 1 Sv (100 rem.) Radiation therapy patients often experience it as a side effect of high-level exposures to singular areas. Radiation sickness may cause nausea (from cell damage to the intestinal lining), and additional symptoms such as fatigue, vomiting, increased temperature, and reduced white blood cell count.

#### **Acute Dose to the Whole Body**

Recovery from an acute dose to the whole body may require a number of months. Whole body doses of 5 Sv (500 rem) or more may result in damage too great for the body to recover.

**Example:** 30 firefighters at the Chernobyl facility lost their lives as a result of severe burns and acute radiation doses exceeding 8 Sv (800 rem.)

Only extreme cases (as mentioned above) result in doses so high that recovery is unlikely.

#### **Acute Dose to Part of the Body**

Acute dose to a part of the body most commonly occur in industry (use of X-ray machines), and often involve exposure of extremities (hand, fingers, etc.). 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 better than acute doses because only a small number of cells need repair at any one time. Also, since radical physical changes do not occur as with acute doses, the body has more time to replace dead or non-working cells with new ones.

#### **Genetic Effects**

Genetic effects involve changes in chromosomes or direct irradiation of the fetus. Effects can be somatic (cancer, tumors, etc.) and may be heritable (passed on to offspring).

#### **Somatic Effects**

Somatic effects apply directly to the person exposed, where damage has occurred to the genetic material of a cell that could eventually change it to a cancer cell. It should be noted that the chance of this occurring at occupational doses is very low.

#### **Heritable Effects**

This effect applies to the offspring of the individual exposed, where damage has occurred to genetic material that doesn't affect the person exposed, but will be passed on to offspring.

To date, only plants and animals have exhibited signs of heritable effects from radiation. This data includes the 77,000 children born to the survivors of Hiroshima and Nagasaki. The studies performed followed three generations, which included these children, their children, and their grandchildren.

### **6.3. Biological Damage Factors**

Biological damage factors are those factors that directly determine how much damage living tissue receives from radiation exposure, including:

- **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 area exposed, the greater the biological effects
- **Cell sensitivity**: rapidly dividing cells are the most vulnerable

Individuals sensitive to ionizing radiation:

- Developing embryo/fetus is the most sensitive
- Children are the second most vulnerable
- The elderly are more sensitive than middle-aged adults
- Young to middle-aged adults are the least sensitive

Bruker analyzers, if used in accordance with manufacturer's instructions, do not pose any significant threat of exposure to the operator. Because an embryo/fetus is most susceptible to ionizing radiation, special rules have been developed for pregnant workers. See Section 7.2.1.



## 7. 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.

### 7.1. 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.

| Average Estimated Days Lost By Industrial Occupations |                     |
|---|---------------------|
| Occupation*   | Estimated Days Lost |
| Mining/Quarrying                                      | 328                 |
| Construction  | 302                 |
| Agriculture   | 277                 |
| Transportation/Utilities                              | 164                 |
| 5 rem radiation dose 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

The comparison of health and industrial risks illustrates the fact that no matter what you do there is always some associated risk. For every risk there is some benefit, so you as the worker must weigh these risks and determine if the risk is worth the benefit. Exposure to ionizing radiation is a consequence of the regular use of many beneficial materials, services, and products. By learning to respect and work safely around radiation, we can effectively manage our exposure.

### 7.2. Radiation Dose Limits

To minimize risks from the potential biological effects of radiation, regulatory agencies and authoritative bodies have established radiation dose limits for occupational workers. These limits apply to those working under the provisions of a specific license or registration.

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.



Your employer may have additional guidelines and set administrative control levels. Each employee should be aware of such additional requirements to do their job safely and efficiently. The limits described below have been developed based on information and guidance from the International Commission on Radiological Protection (ICRP-1990), the Biological Effects of Ionizing Radiation (BEIR) Committee, the US Environmental Protection Agency (EPA) and the National Council of Radiation Protection (NCRP). For an XRF analyzer using an X-ray tube as the source, any requirement on dose limits for the operators would be established by the appropriate regulatory agency.

| Annual Occupational Dose Limits                                 |               |        |
|---|---------------|--------|
| Exposed Area  | International | U.S.   |
| Whole Body  | 20 mSv*       | 5 rem  |
| Extremities   | 500 mSv       | 50 rem |
| Organs or Tissue<br><i>(Excluding lens of the eye and skin)</i> | 500 mSv       | 50 rem |
| Lens of the Eye   | 150 mSv       | 15 rem |

\*Averaged over 5 years

**7.2.1. Declared Pregnant Worker**

A female radiation worker may inform her supervisor of her pregnancy, in writing, at which time she becomes a Declared Pregnant Worker. The employer should then provide the option of a mutually agreeable assignment of work tasks, without loss of pay or promotional opportunity, such that further radiation exposure will not exceed the dose limits as shown in the following table for the declared pregnant worker.

| Radiation Limits for Visitors, Public, and Pregnant Workers |   |
|---|---|
| International and US Limit                                  | 1 mSv (100 mrem) per year   |
| Pregnant Worker (International Limit)                       | 2 mSv (200 mrem) to abdomen during remainder of gestation period after declaration  |
| Pregnant Worker (US Limit)                                  | Declared Pregnant Worker (embryo / fetus) - 0.5 rem / 9 months (≈ 0.05 rem / month) |

**8. Measuring Radiation**

Because we cannot detect radiation through our senses, special devices may be required in some jurisdictions for personnel operating an XRF 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.

The following information may apply to personnel using a hand-held XRF analyzer in jurisdictions where dosimetry is required:

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

## 8.1. Dosimeters

While there is variation between dosimeters, and from one type to another, most dosimeters operate in a similar way. Read the instrument user manual to understand how to operate and interpret the measurements provided by the instrument.

### Whole Body Dosimeter

A Thermoluminescent Device (TLD) or Optically Simulated Luminescence (OSL) whole body dosimeter is used to measure both shallow and deep penetrating radiation doses. It is normally worn between the neck and waist. The measured dose recorded by this device may be used as an individual's legal occupational exposure.

### Finger Ring

A finger ring is a TLD in the shape of a ring, which is worn by workers to measure the radiation exposure to the extremities. The measured dose recorded by this device may be used as the worker's legal occupational extremity exposure.

## 8.2. Survey Meters

Some jurisdictions require the monitoring of output from handheld analyzers by the use of a survey meter, which detects radiation in real time. Survey meters generally consist of a detector and a read-out display. The two most commonly used survey meters are the **ionization chamber** and the **Geiger-Mueller (GM) Tube**.

The ionization chamber is inefficient (30-40% efficiency is typical), as some radiation may pass through the chamber without creating enough ion pairs for proper measurement; the GM tube is much more sensitive; however, in both cases, it is essential that the meters be properly calibrated for the energy range emitted by the handheld device, generally in the 5.0-50kV range. Improper calibration may result in incorrect readings as the radiation emitted by a handheld device is low energy. Consult the meter's user guide for proper calibration.

## 9. Exposure Reduction (ALARA)

While dose limits and administrative control levels already ensure very low radiation doses, it is possible to reduce these exposures even more. The main goal of the ALARA program is to reduce ionizing radiation doses to a level that is As Low As Reasonably Achievable (ALARA). ALARA is designed to prevent unnecessary exposures to employees, the public, and to protect the environment. It is the responsibility of all workers, managers, and safety personnel alike to ensure that radiation doses are maintained ALARA.

There are three basic practices to maintain external radiation ALARA: **Time, Distance, and Shielding**.

### Time

The first method of reducing exposure is to limit the amount of time spent in a radioactive area. Generally, the shorter the time, the lesser the amount of exposure.

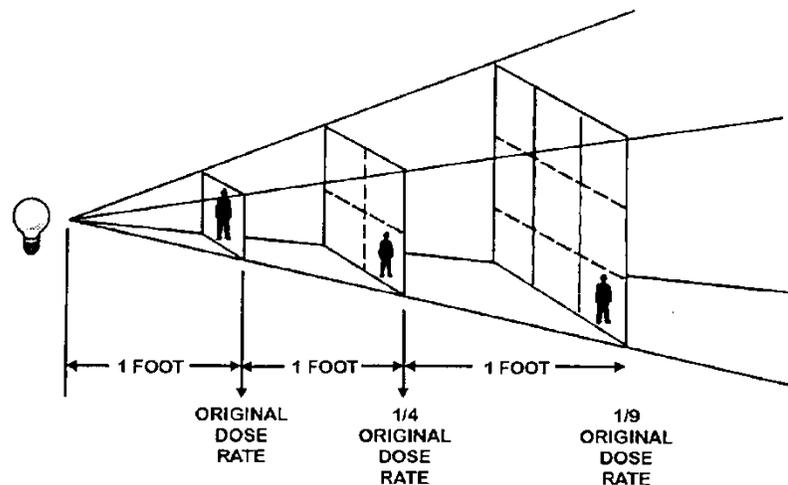
The effect of time on radiation could be stated as

$$\text{Dose} = \text{Dose Rate} \times \text{Time}$$

**Example:** If 1 hour of time in an area results in 1 mSv (100 mrem) of radiation, then 1/2 an hour results in 0.5 mSv (50 mrem), and 1/4 an hour would result in 0.25 mSv (25 mrem), and so on.

### 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. The greater the distance, the amount of radiation received is reduced. This method can best be expressed by the Inverse Square Law.



The inverse square law states that doubling the distance from a point source reduces the dose rate (intensity) to 1/4 of the original. Tripling the distance reduces the dose rate to 1/9 of its original value. Expressed mathematically:

$$C \times \frac{D_1^2}{D_2^2} = I$$

Where:

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

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

### **Shielding**

The third, and perhaps 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.

As stated earlier, 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.

***Example:*** A cubic foot of lead is heavier than the same volume of concrete, and so it would also be a better shield.

Although shielding may provide the best protection from radiation exposure, there are still several precautions to keep in mind when using TRACER XRF devices:

- 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.
- Scattered radiation may bounce around corners and reach nearby individuals, whether or not they are directly in line with the test location.

***WARNING:*** To avoid inadvertent exposure to others, the operator should ensure that there is no one on the other side of the wall or barrier when using an XRF analyzer.