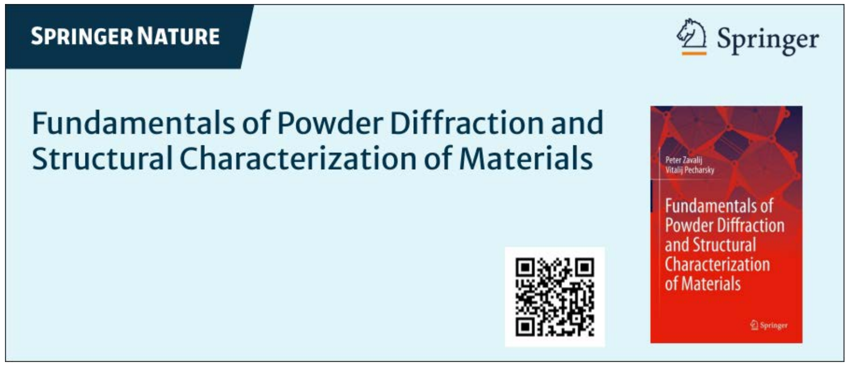

APPENDIX

A. RADIATION SAFETY

The information contained in this section deals with radiation safety for users of analytical X-ray systems. It was developed by the Environmental, Safety, Health and Assurance Office of the United States Department of Energy Ames Laboratory.[1] In the content of this book it is intended to raise awareness about the potential dangers associated with the continuous or acute exposure to X-ray radiation and has no legal force. Each workplace where analytical X-rays are used should have a set of established policies and procedures, which must be strictly enforced and are designed to protect both the operator(s) of analytical X-ray instruments and nearby personnel from X-ray exposure.[2]

A.1 Radiation Quantities and Terms

X-rays transfer their energy to matter through chance encounters with bound electrons or atomic nuclei. These random encounters result in the ejection of energetic electrons from the atom. Each of the electrons liberated goes on to transfer its energy to matter through many direct ionization events (i.e. events involving collisions between charged particles). Since X-rays transfer energy in this indirect manner, they are referred to as indirectly ionizing radiation. Because the encounters of X-ray photons with atoms are by chance, a given photon has a finite probability of passing completely through the medium it is traversing. The probability that a photon will pass completely through a medium depends upon numerous factors including the energy of the X-rays and the medium's chemical composition and thickness.

The following quantities and terms are essential to the description and measurement of various forms of ionizing radiation.

– Exposure. It is a measure of the strength of a radiation field at some point. It is usually defined as the amount of charge (i.e., sum of all ions of one sign) produced in a unit mass of air when the interacting photons are completely absorbed in that mass. The most commonly used unit of exposure is the Roentgen, R, which is defined as that amount of radiation which produces 2.58×10^{-4} coulombs of charge per kilogram (SI units) of dry air. In cases where exposure is to be expressed as a rate, the unit would be R/h or, more commonly, mR/h.

– Absorbed dose. It is the amount of energy passed on by radiation to a given mass of any material. The most common unit of absorbed dose is the rad, which is defined as a dose of

1 The document was kindly provided by Mrs. Kate Sordelet.

2 An overview of precautions against radiation injury is also given by D.C. Creagh and S. Martinez-Carrera in the International Tables for Crystallography, vol. C, Second edition, A.J.C. Wilson and E. Prince, Eds., Kluwer Academic Publishers, Boston/Dordrecht/ London (1999) p. 949.

100 ergs of energy per gram of the material in question (SI unit is the gray, 1 Gy = 1 J/kg). The absorbed dose may also be expressed as a rate with units of rad/h or mrad/h.

– Dose equivalent. Although the biological effects of radiation are dependent upon the absorbed dose, some types of particles produce greater effects than others for the same amount of transferred energy. In order to account for these variations when describing human health risk from radiation exposure, the quantity dose equivalent is used. This is the absorbed dose multiplied by certain quality and modifying factors indicative of the relative biological-damage potential of the particular type of radiation. The unit of dose equivalent is the rem or, more commonly, mrem (SI unit is the sievert, 1 Sv = 1 J/kg). Dose equivalent may likewise be expressed as a rate with units of rem/h or mrem/h. For X-ray exposures, the numerical value of the rem is essentially equal to that of the rad.

– Shielding. It is any material, which is placed around or adjacent to a source of penetrating radiation for the purpose of attenuating the exposure rate from the source. For shielding X-rays, materials composed of high atomic number elements such as lead are highly effective.

– Half-value layer. It is that thickness of a given material (i.e. shielding) required to reduce the exposure rate from a source of gamma or X-rays to one-half of its unshielded value.

A.2 Biological Effects of Ionizing Radiation

The energy deposited by ionizing radiation as it interacts with matter may result in the breaking of chemical bonds. If the irradiated matter is living tissue, such chemical changes may result in an altered structure or function of constituent cells. The effects of ionizing radiation described at the level of the human organism can be divided broadly into two categories: stochastic and non-stochastic effects.

As implied from the name, stochastic, these are effects that occur by chance. Stochastic effects caused by ionizing radiation consist primarily of genetic effects and cancer. As the dose to an individual increases, the probability that cancer or a genetic effect will occur also increases. However, at no time, even for high doses, is it certain that cancer or genetic damage will result. Similarly, for stochastic effects, there is no threshold dose below which it is relatively certain that an adverse effect cannot occur. In addition, because stochastic effects can occur in unexposed individuals, one can never be certain that the occurrence of cancer or genetic damage in an exposed individual is due to radiation.

Unlike stochastic effects, non-stochastic effects are characterized by a threshold dose below which they do not occur. In addition, the magnitude of the effect is directly proportional to the size of the dose. Furthermore, for non-stochastic effects, there is a clear causal relationship between radiation exposure and the effect. Examples of non-stochastic effects include sterility, erythema (skin reddening), ulceration, and cataract formation. Each of these effects differs from the other in both its threshold dose and in the time over which this dose must be received to cause the effect (i.e. acute vs. chronic exposure).

The effect of ionizing radiation upon humans or other organisms is directly dependent upon the size of the dose received. The dose, in turn, is dependent upon a number of factors including the strength of the source, the distance from the source to the affected tissue, and the time over which the tissue is irradiated. The ability of a given dose of ionizing radiation to cause health effects is influenced by the rate at which the dose is imparted. Because of various repair processes, which occur within the human body, a given dose of radiation in excess of that needed to produce a particular non-stochastic effect may, in fact, not produce such an effect if the dose is imparted over a relatively long period of time (i.e. chronic exposure). It is conservatively assumed, however, that dose rate is not a critical factor in controlling the probable occurrence of stochastic effects such as cancer or genetic damage.

Long-term exposures to relatively low levels of ionizing radiation are referred to as chronic exposures. Such exposures have little potential for inducing non-stochastic health effects and are of concern because of their potential for initiating cancer or genetic damage. Short-term exposures to relatively high levels of ionizing radiation are referred to as acute exposures. Such exposures have the potential for producing both non-stochastic effects (e.g. erythema, epilation, and ulceration) as well as stochastic effects (e.g. cancer) in the irradiated tissue.

The effectiveness of a given dose of external radiation in causing biological damage is dependent upon the portion of the body irradiated. For example, because of differences in the radiosensitivity of constituent tissues, the hand is far less likely to suffer biological damage from a given dose of radiation than are the gonads. Similarly, a given dose to the whole body has a greater potential for causing adverse health effects than does the same dose to only a portion of the body.

A.3 Exposure Limits

Concern over the biological effects of ionizing radiation began shortly after the discovery of X-rays. From that time to the present, numerous recommendations regarding occupational exposure limits have been proposed and modified by various radiation protection groups, the most important being the International Commission on Radiological Protection (ICRP). These guidelines have, in turn, been incorporated into regulatory requirements for controlling the use of materials and devices emitting ionizing radiation.

In general, the guidelines established for radiation exposure have had as their principle objectives: (1) the prevention of acute radiation effects (e.g., erythema, sterility), and (2) the limiting of the risks of late, stochastic effects (e.g., cancer, genetic damage) to “acceptable” levels. Numerous revisions of standards and guidelines have been made over the years to reflect both changes in the understanding of the risk associated with various levels of exposure and changes in the perception of what constitutes an “acceptable” level of risk.

Current guidelines for radiation exposure are based upon the conservative assumption that there is no safe level of exposure. In other words, even the smallest exposure has some probability of causing a late effect such as cancer or genetic damage. This assumption has led to the general philosophy of not only keeping exposures below recommended levels or regulatory limits but of also maintaining all exposures “as low as is reasonably achievable” (ALARA). This is a fundamental principle of current radiation safety practice.

Many of the recommendations of the ICRP and other radiation protection groups regarding radiation exposure have been incorporated into regulatory requirements by various countries. For the U.S. Department of Energy facilities, radiation exposure limits are found in Title 10, Part 835 of the Code of Federal Regulations (10CFR835). Table A.1 provides a summary of the dose limits for occupational external exposures.

Table A.1. Summary of dose limits [10 CFR 835.202, 1003(a)(1), (a)(2)]

Type of exposure	Limit
General employee: whole body (internal + external)	5 rem/year
General employee: lens of the eye (external)	15 rem/year
General employee: hands, arms below the elbows, feet, legs below the knee	50 rem/year
General employee: any organ or tissue (other than lens of the eye) and skin	50 rem/year
Declared pregnant worker: fetus/embryo (internal and external)	0.5 rem/ges-tation period
Minors: whole body (internal and external)	0.1 rem/year
Minors: lens of the eye (external), skin and extremities	10 % of general employee limit

For whole body exposure, the non-occupational exposure limit is 100 mrem/year. This is in addition to the 360 mrem/yr received, on average, by individuals in the U.S. from natural background radiation and manmade radiation sources. The 100 mrem/year limit also applies to individuals under age 18 who work in the vicinity of radiation sources.

A.4 Radiation Hazards of Analytical X-ray Systems

Because they utilize extremely high intensity X-ray beams, analytical X-ray systems have the potential for posing significant hazards if operated inappropriately. Radiation exposures can result not only from the primary beam but also from scattered (or diffracted) rays and secondary radiation from the sample or shielding material.

The X-rays utilized most commonly in analytical systems have wavelengths in the range of 0.5 to 10 angstroms. These are often referred to as soft X-rays because of the ease by which they are absorbed in matter. While this characteristic enables soft X-rays to be readily shielded (generally requiring only a few millimeters of lead or iron), it also makes them particularly hazardous since they are highly absorbed even by soft tissue.

The primary beams from analytical X-ray systems are generally well collimated with beam diameters of less than one centimeter. Because of their intensity and their high degree of absorption in tissue, they can produce severe and permanent local injury from exposures of only a fraction of a second.

Exposure to the primary beam of powder diffraction units is a major concern. In fact, the greatest risk of acute accidental exposures from analytical systems occurs in manipulations of the sample to be irradiated by the direct beam in diffraction studies. Exposure rates on the order of 10,000 R/s ($\sim 4\times10^7$ R/h) can exist at the tube housing port. At these levels, erythema would be produced from exposures of only 0.03 second and permanent injury could be inflicted in only 0.1 second. The fingers, of course, are the part of the body most at risk from such high exposures.

For X-ray diffraction systems, the diffracted beam is also small and focused with an intensity of up to 80 R/h (~22 mR/s). Prolonged or repeated exposures to a beam of this intensity could result in an individual exceeding the annual dose limit for the particular tissue irradiated.

Through interactions with the sample and shielding material, the primary beam in diffraction systems often produces diffuse patterns of scattered and secondary X-rays in the environment around the equipment. Exposure rates of 150 mR/h near the shielded sample are not uncommon.

A.5 Hazard Control Measures for Analytical X-ray Systems

Requirements for controlling potential hazards associated with analytical X-ray systems are specified in most states by law. For example, at Ames Laboratory these requirements are detailed in the Radiological Protection Program or Policy #10202.003, "Analytical X-ray Safety". Portions of these hazard control and safety measures are summarized below.

Equipment requirements.

- Beam entry shut-off device. A device which prevents the entry of any portion of an individual's body into the primary beam path or which causes the beam to be shut off upon entry into its path shall be provided on all open-beam configurations.
- Shutters. On open-beam configurations, each port on the source housing shall be equipped with a shutter that cannot be opened unless a collimator or coupling has been connected to the port.
- Housing interlock. Each X-ray tube housing shall be equipped with an interlock that shuts off the tube if the tube is removed from the housing or if the housing is disassembled.
- Shielding provided by housing. Each X-ray tube housing shall be constructed so that, with all shutters closed, the radiation, measured at a distance of five centimeters from its surface, is not capable of producing a dose in excess of 2.5 mrem in one hour.
- Warning lights. An easily visible warning light with the words "X-RAY ON" shall be located near any switch that energizes an X-ray tube and shall be illuminated only when the tube is energized.
- Labeling. All analytical X-ray equipment shall be labeled with a readily discernible sign bearing the radiation symbol and the words: (1) "CAUTION - HIGH INTENSITY X-RAY BEAM" on the X-ray source housing; and (2) "CAUTION RADIATION - THIS EQUIPMENT PRODUCES RADIATION WHEN ENERGIZED" near any switch that energizes the X-ray tube.

Area requirements.

- Radiation levels. The components of an analytical X-ray system shall be arranged and shall be sufficiently shielded to ensure that radiation levels near the components cannot result in an individual receiving a dose in excess of 2 mrem in any one hour.
- Surveys. Radiation surveys of all analytical X-ray systems sufficient to show compliance with the radiation levels established in the previous item must be performed: (1) upon installation of the equipment and at least every twelve months thereafter; (2) following any change in the number, type, or arrangement of components in the system; (3) following any maintenance requiring the disassembly or removal of a system component.

- Posting. Each room containing analytical X-ray equipment shall be conspicuously posted with a sign bearing the radiation symbol and the words “CONTROLLED AREA.” The interlocked barriers surrounding the X-ray systems shall be posted as a “BUFFER AREA”, and the area immediately adjacent to all X-ray beam ports, whether open beam or closed beam, shall be posted with a sign which reads “CAUTION [OR DANGER] - HIGH RADIATION AREA”.

<u>Operating Requirements</u>.

- Procedures. Normal operating procedures shall be written and available to all analytical X-ray equipment workers.
- Bypassing safety devices. No individual shall bypass a safety device or interlock unless the individual has obtained written approval of the radiation safety officer.
- Altering system components. No operation involving the removal or alteration of shielding materials, tube housing, shutter, collimators, or beam stops shall be performed until it has been determined that the beam is off and will remain off until safe conditions have been restored.
- Personnel monitoring requirements. At the Ames Laboratory, the Health Physics Group issues ring dosimeters to all users of X-ray diffraction devices and, if requested by the user, whole body badges (Fig. A.1) in addition to the extremity dosimeters. Dosimetry is used to provide an indication of the amount of external radiation exposure the wearer has received, and must be worn at all times when using the equipment. The dosimetry will not be issued to any individual until the required safety training has been completed. Dosimeters do not protect from radiation exposure – they are only used to determine the received dose, if any.

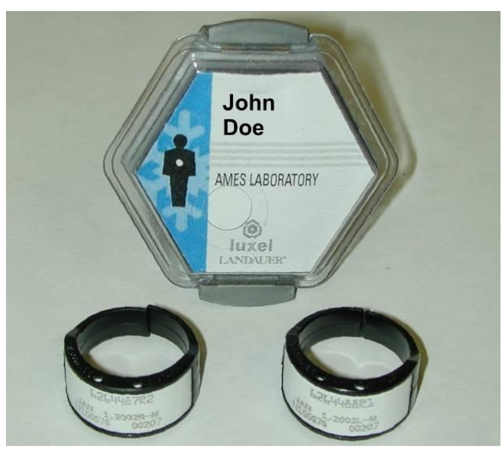

Fig. A.1. Whole body badge (top) and finger dosimeters (bottom) issued to all trained analytical X-ray users at the US DOE’s Ames Laboratory.

- Each individual who wishes to be authorized to use analytical X-ray equipment at the Ames Laboratory must first receive training concerning the radiation hazards associated with the use of the equipment, the function and importance of the equipment’s safety devices, proper operating procedures, and procedures to follow in the event of a suspected radiation exposure.