Hazards in the Use of X-Ray Analytical Instrumentation

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Abstract
This paper outlines the potential hazards in the use of X-ray analytical instrumentation and is composed of two major sections. The first section defines the terminology employed and outlines the causes and effects of radiation damage. Also covered is the national recognition of the problem which has led to present day legislation of dose levels. The second part is a verbatim copy of the report MORP 68-14 *Radiation Safety Recommendations for X-ray Diffraction and Spectrographic Equipment* by Moore and McDonald, and is reproduced by kind permission of the United States Department of Health, Education and Welfare, Bureau of Radiological Health.

Hazards in the Laboratory
The analytical chemist is generally well aware of the potential dangers in the use of the tools of his trade. Any laboratory worker, however inexperienced, has some degree of respect for the reagents with which he comes into contact. He learns, at a very early laboratory age, that strong acids burn, that arsenic salts poison and that many volatile organic solvents are potential fire hazards. Yet for all this, people are burnt and poisoned, and there are laboratory fires. In many cases the cause may perhaps be due to sheer ignorance, but statistics show that far more likely causes are carelessness and foolish decisions like the one to ‘forget the safety glasses this time’. In these modern times of sophisticated automatic analytical instruments, new potential dangers to life and limb are to be found in misuse of the shiny boxes which offer ‘automatic analysis and many hours of unattended operation’. Of special note in this category are those instruments which utilize ionizing radiations, and of particular interest in this paper, to those which utilize X-radiation.

Hazards in the use of X-radiation
X-rays are energetic electromagnetic radiations that ionize matter with which they interact, by ejecting electrons from their atoms. The extent of the ionization, absorption and molecular change on a material depends on the quantity (radiation flux and intensity) and the quality (the spectral distribution of the photon energy) of the radiation. Living organisms which are exposed to various doses of ionizing radiation, can be injured by such exposures and death may result from severe exposures. It is imperative that all operators of X-ray instruments be knowledgeable in their use in order to protect themselves from injury.

Since the very early days of X-ray analysis accidents have occurred, but only over the past few years has the magnitude of the problem been recognized on a national level. Ironically enough, it is not the potential hazard in the use of analytical X-ray instrumentation that has brought about this recognition, but the advent of colour television. Radiation levels from the earlier colour television receivers were found to be well in excess of ‘acceptable limits’, and in most countries, government legislation followed swiftly. Many countries now have government committees who have within their responsibility the establishment of acceptable limits of exposure to ionizing radiations, and equally important, have the power to enforce adherence to these conditions. The following is a short extract from the hearings before a sub-committee of the committee on appropriations of the United States House of Representatives, which took place on April 18th, 1972.

“Enforcement of the Radiation Control for Health and Safety Act”

Scope of the Act. The Radiation Control for Health and Safety Act, Public Law 90-602, became effective on October 18, 1968, after more than 14 months of extensive hearings involving numerous representatives of government, industry, and the public. Its passage marked the beginning of a new era in the relationship between Federal health authorities and the $25 billion electronic products industry. The Act was enacted in response to a growing concern over radiation exposure from consumer electronic products. These exposures emanate from a wide variety of commercially available products which emit a broad spectrum of radiant energies. In some cases the radiation is intentionally produced (medical X-ray equipment), and in other cases the exposure is completely unintentional (X-radiation from television receivers). The provisions of the Act apply to all electronic products manufactured or assembled within or imported into the United States and its territories on or after October 18, 1968. The term ‘electronic product’ is defined as any manufactured electronic device which is capable of emitting electronic product radiation, or any manufactured article intended for use as a component of such a device which can affect the emitted radiation. ‘Electronic product radiation’, as defined by the Act, includes both ionizing and non-ionizing electromagnetic and particulate radiation as well as sonic, infrasonic, and ultrasonic waves. The broad scope of these definitions is necessary in order to cover effectively the wide range of complex, radiation-emitting electronic products that are commercially available for consumer, medical, industrial and research applications.

Responsibilities. The primary responsibility for implementing and enforcing the provisions of the Act has been delegated to the Food and Drug Administration's Bureau of Radiological Health. This responsibility entails the establishment of an electronic product radiation control program that involves both formal regulatory activities and a variety of efforts in basic research and development. The law specifically directs the Bureau of Radiological Health to study the conditions of exposure to electronic product radiation and the resulting biological effects. The Bureau also has established and is maintaining liaison with interested persons both inside and outside of government and is supporting research and training in methods of minimizing unnecessary exposure to electronic product radiation. While these general activities are of considerable importance in their own right, they are intended primarily to support the central purpose of the law, which is to regulate and control the emission of electronic product radiation which represents a hazard to human health and safety.

Authorities. The principal regulatory authorities provide the Bureau of Radiological Health the power to require manufacturers of electronic products to correct any defects relating to the safety of use of their products and the authority to establish and enforce radiation safety performance standards for specific types of electronic products. These are the main regulatory powers used by the Bureau in administering its electronic product radiation control program. However, in order to facilitate this effort, the Bureau also has the authority to require manufacturers of electronic products to maintain testing and distribution records, submit various reports, and, if good cause is shown, permit inspection of their manufacturing facilities. The detailed regulations for implementing the Act and all performance standards established under it are published in Title 42, Part 78 of the Code of Federal Regulations.

Units of measurement for ionizing radiation

The standard unit for measuring the quantity of ionizing radiation is the roentgen (R). The roentgen is defined as a radiation flux that will produce 2.08×10^9 ion pairs/cm^3 in air at Standard Temperature and Pressure. This number of ion pairs is equivalent to an energy of 84 ergs.

The absorption of the radiation depends on the nature of the absorbing material, thus the actual energy deposited (i.e. ionization produced in the material) can differ considerably for different materials. For this reason, two other units of measurement were devised which measure only the energy deposited in the absorbing material. One of these is the rad (roentgen-absorbed-dose) which is defined as that amount of ionizing radiation that deposits 100 ergs/gm of energy in the absorber. The second unit is the rem (roentgen-equivalent-man) which is the absorbed dose in rads corrected for the equivalent absorption of the radiation in living tissue. Thus the dose in rem = (dose in rad x RBE) where the RBE is the relative biological effectiveness of the radiation.

Hence, whereas the roentgen is defined and measured in terms of ion pairs produced in air, the rad and rem are defined and measured in terms of the energy deposited in the absorbing substance. For all practical purposes radiation produced by analytical X-ray instruments (diffraction and spectrographic equipment operating at less than 100 kV) = Dose in R = Dose in rad = Dose in rem.

Radiation monitoring and permitted dose

The common measurement of X-ray intensity is the R/hr (roentgen per hour) or mR/hr (milliroentgen per hour). By multiplying the radiation intensity by the total exposure time, the total dose is obtained.

Standard survey meters are of two types, Geiger Counters and Ionization Chambers. The Geiger Counter survey meter counts individual photons which, by appropriate conversion, can be expressed in roentgens. Conversely, the Ionization Chamber survey meter actually measures the ion pairs produced by the radiation and gives a direct measure in roentgens. Note, however, that both the Geiger and Ionization survey meters must be calibrated with X-ray photons of similar energy to those for which the survey meter is called upon to monitor. Otherwise, the instrument will read incorrectly for X-rays of either too high or too low energy.

Normal background radiation levels are of the order of 0.01–0.1 mR/hr. At this rate, one would expect to receive 0.05 x 24 = 1.2 mR of exposure per day or 1.2 mR/day x 365, approximately 500 mR per year from terrestrial radiations. Studies have shown that an occupational exposure of 5 rem per year or 3 rem for any 13-week interval is considered acceptable for regular safe operation of X-ray equipment.

Skin erythema (reddening of the skin) occurs with a local dose of approximately 300 R. Skin destruction (burns) results from doses above 500 R. This order of magnitude of dose required to damage living tissue (in a short exposure) is large by normal background conditions. However, realizing that X-ray diffraction and spectrographic tubes generate dose rates between 100 000 and 1 000 000 R/hr, only a short exposure to the primary beam of analytical instruments is required to cause severe skin burns.

Develop good radiation safety habits

There are several precautions that operators of X-ray equipment can employ in order to reduce the possibility of a radiation accident.

Thorough radiation surveys should always be performed on newly installed or modified equipment. In addition, a survey meter should be kept near the equipment at all times, such that casual surveys can be performed frequently. It should never be assumed that the equipment has been left in a safe condition by a precious operator or by a serviceman.

A film badge should be worn at the proper height and facing the radiation source. The film badge essentially establishes and records an exposure history for each person, but in addition it acts as a constant reminder that X-radiation can be hazardous. A 2- or 4-week cycle time for film badges is desirable. Analytical X-ray equipment is manufactured with numerous safety devices and interlocks, and these should be checked frequently. These protection devices should never be disabled unless special precautions are taken. Finally, one should be sure that equipment meets and preferably exceeds the local radiation safety standards.

Legal and moral responsibilities

The legal responsibilities governing organizations making, selling or using X-ray analytical equipment vary from country to country. At this point in time, there is no international agreement. Even within a given country, the degree of enforcement of what law there is, may vary from one local government to the next (See U.S. Bureau of Standards Handbook 111). In the United States, the responsibility for the establishment and enforcement of safety levels pertaining to the manufacture of X-ray diffraction and spectrographic equipment falls under the jurisdiction of the U.S. Department of Health, Education and Welfare. Permission has been given to us to reproduce in full the report MORP 68-14 *Radiation Safety Recommendations for X-ray Diffraction and Spectrographic Equipment* dated October 1968, by T.M. Moore and D.J. McDonald. In a foreword to the report, it is stated that ……

> 'the 'Radiation Control for Health and Safety Act of 1968' (Public Law 90-602) effective October 18, 1968, provides that the Secretary of Health, Education, and Welfare shall establish an 'electronic product radiation control program which shall include the development and administration of performance standards to control the emission of electronic product radiation'. X-ray diffraction and spectrographic equipment, which are discussed in this report, are included within the scope of Public Law 90-602. However, the guides suggested in this report were developed prior to passage of the law and should not be confused with the performance standards authorized under the new law. Nonetheless, these guides may be useful for the subsequent development of regulatory standards, if the Secretary determines that such standards are necessary for the protection of the public health and safety……'.

It is strongly recommended that all workers in the field check the appropriate regulations pertaining to their own situation. Where local regulations are apparently not defined or enforced, the following report should act as a good guide line.

Introduction to Report MORP 68-14

Until the past few years very little attention has been given to the radiation hazards associated with the use of X-ray diffraction and spectrographic equipment. However, recent studies show that a significant number of reported radiation injuries have resulted from accidents involving such equipment.[1–6]

Although there are published reports dealing with radiation protection procedures and apparatus designs, there is a lack of generally accepted standards or recommendations for X-ray diffraction and spectrographic equipment. For these reasons, the Medical and Occupational Radiation Program of the National Center for Radiological Health, in cooperation with the Office of Radiological Health of the Pennsylvania Department of Health, has formulated the following recommendations which may serve as a guide to those persons or agencies concerned with this problem. Existing guides have been liberally excerpted. [7–12]

Those recommendations containing the word 'shall' are considered necessary to meet minimal standards of protection. Those using the word 'should' are considered advisory, and are to be applied when practical.

What now follows is a verbatim reproduction of the report.

Definitions

Analytical X-ray equipment: Any device which utilizes X-rays for the purpose of examining the microstructure of materials. This includes all types of X-ray diffraction and spectrographic equipment.

Dose equivalent: A quantity that expresses on a common scale for all radiations the irradiation incurred by exposed persons. It is defined as the product of the absorbed dose in rads and certain modifying factors. The unit of dose equivalent is the rem. (For radiation protection purposes in these recommendations, the dose equivalent in rems may be considered numerically equivalent to the absorbed dose in rads and the exposure in roentgens.)

Interlock: A device for precluding access to an area in which radiation is present by automatically reducing the exposure rate upon entry by personnel or parts of their body.

Leakage radiation: All radiation coming from within the X-ray tube housing except the primary radiation beam.

Maximum permissible dose equivalent: The maximum dose equivalent that a person or specified parts thereof shall be allowed to receive in a stated period of time. (See Appendix A.)

Open beam X-ray equipment: An X-ray producing device designed in such a way that the primary beam is not completely enclosed by the tube housing-apparatus complex during normal operation.

Primary radiation beam: The unscattered or undeflected X-ray beam which has emerged from a port in the X-ray tube housing.

Radiation controlled area: A defined area in which the occupational radiation exposure of personnel is under the supervision of an individual in charge of radiation protection.

This includes control of access, occupancy, and working conditions for radiation protection purposes.

Scattered radiation: Radiation that, during passage through matter, has been deviated in direction.

Stray radiation: The sum of leakage and scattered radiation.

Tube housing-apparatus complex: Those parts of an analytical X-ray device in which X-rays are produced and utilized. This includes the X-ray tube housing, shutter or port assemblies, collimators, cameras, goniometers, and electronic radiation detectors. This is not intended to include such components as transformers, control panels, or temporary shielding.

X-ray Diffraction equipment: An analytical X-ray device in which an X-ray beam (usually monochromatic) is made to strike a specimen, causing a portion of the beam to be diffracted. Measurements of certain parameters of the diffracted beam may be used to provide qualitative and / or quantitative information about the specimen.

X-ray spectrographic (fluorescence) equipment: An analytical X-ray device in which a polychromatic X-ray beam is made to strike a specimen, producing X-ray fluorescence which is characteristic of the specimen. A portion of the fluorescent radiation is directed into an analyzing crystal where it is diffracted. The wavelength of interest may then be monitored by a properly positioned detector to provide qualitative and / or quantitative analysis of the specimen.

Recommendations

Administrative responsibilities

1. For each facility a person shall be appointed to be responsible for radiation safety. This person, designated the radiation protection supervisor or radiation safety officer, shall be responsible for the following:

   Comment: The radiation protection supervisor (who may be the operator) should be familiar with the basic principles of radiation protection and the particular hazards associated with the operation of X-ray diffraction and spectrographic equipment, although he may consult with appropriate experts for detailed advice. The radiation protection supervisor should clearly have authority over matters involving radiation safety, and ideally should be a member of the management staff.

   (a) Insuring that operational procedures pertaining to radiation safety are established and carried out so that the radiation exposure of each worker is kept as far below the maximum permissible dose equivalent as is practical.

   Comment: The primary objective in establishing maximum permissible dose equivalent values for occupational exposure is to keep the exposure of the radiation worker well below a level at which adverse effects are likely to be observed during his lifetime. Another objective is to minimize the incidence of genetic effects for the population as a whole. While the risk to individuals exposed to the maximum permissible dose equivalent is considered to be very small, the risk increases gradually with the dose received. For this reason, it is desirable to keep radiation exposures as low as is practical with due consideration to feasibility and efficiency of operation.

   (b) Providing instruction in safety practices for all personnel who work with or near X-ray diffraction and spectrographic equipment.

   (c) Maintaining a system of personnel monitoring.

   (d) Arranging for establishment of radiation control areas, including placement of appropriate radiation warning signs and / or devices.

   (e) Providing for radiation safety inspection of X-ray diffraction and spectrographic equipment.

   (f) Reviewing and approving modifications to X-ray apparatus, including X-ray tube housing, cameras, diffractometers, shielding, and safety interlocks.

   (g) Investigating any case of abnormal radiation exposure to personnel and taking remedial action, if necessary.

   (h) Complying with all applicable Federal, State, and local rules and regulations.

2. No individual shall be permitted to act as an operator of a particular X-ray diffraction or spectrographic machine until such person has:

   (a) Received an acceptable amount of training in radiation safety as approved by the radiation protection supervisor.

   (b) Demonstrated competence to use the machine and radiation survey instruments which will be employed.

   (c) Received the approval of the radiation protection supervisor.

3. The operator of the X-ray diffraction or spectrographic equipment shall be responsible for all operations associated with that equipment, including radiation safety. In particular he shall:

   (a) Keep radiation exposure to himself and others as low as is practical.

   (b) Be familiar with safety procedures as they apply to each machine he operates.

   (c) Wear personnel monitoring devices, if applicable (see Items 10, 11, and 30b).

   (d) Notify the radiation protection supervisor of known or suspected abnormal radiation exposures to himself or others.

Operating procedures

4. Personnel shall not expose any part of their body to the primary radiation beam.

5. Only trained personnel, as approved by the radiation protection supervisor, shall be permitted to install, repair, or make other than routine modifications to the X-ray generating apparatus and the tube housing-apparatus complex.

6. Procedures and apparatus utilized in beam alignment should be designed to minimize radiation exposure to the operator.

   Comment: Particular attention should be given to viewing devices to assure that lenses and other transparent components attenuate the radiation beam to minimal levels. When alignment involves working near the open primary radiation beam, the beam current should be reduced in order to lower exposure rates. If a fluorescent alignment tool is used, dimming the room light will permit a significant reduction in beam current. The fluorescent alignment tool should be long enough to permit the operator's hand to be kept a safe distance from the beam. The operator should be familiar with the manufacturer's recommended alignment procedures and copies of these should be available for reference.
7. Written emergency procedures pertaining to radiation safety shall be established for each facility by the radiation protection supervisor and shall be posted in a conspicuous location near each X-ray diffraction or spectrographic unit. These should list telephone numbers of a physician and the radiation protection supervisor and, as a minimum, should include instructions for the following actions to be taken in case of a known or suspected accident involving radiation exposure.
   (a) Notifying radiation protection supervisor.
   (b) Arranging for medical examination, being sure to notify the examining physician that exposure to low energy X-rays may have occurred.
8. If, for any reason, it is temporarily necessary to alter safety devices, such as bypassing interlocks or removing shielding, such action shall be:
   (a) Specified in writing, approved by the radiation supervisor, and posted near the X-ray tube housing so that other persons will know the existing status of the machine.
   (b) Terminated as soon as possible.
9. Radiation exposure to individuals, either within the radiation controlled area or in its environs, shall be so controlled that the maximum permissible dose equivalent values as set forth by the National Council on Radiation Protection and Measurements (see Appendix A), or Federal, State, and local rules and regulations, are not exceeded.

Personnel monitoring

10. Operators of X-ray diffraction or spectrographic equipment should be provided with finger or wrist radiation monitoring devices. The supplier of the monitoring device should be notified of the energy of the monitored radiation.

    Comment: The decision as to the need for personnel monitoring devices should be made after first evaluating the likelihood that the operator will be working in close proximity to the primary radiation beam, taking into account procedures such as beam alignment and equipment maintenance. The monitoring device should be so located that the body part nearest the primary beam is monitored. For example, if the operator sets up an experiment working primarily with his right hand, a wrist or finger monitor should be worn on that hand. Monitoring devices worn on the chest or abdomen may provide an indication of the amount of stray radiation to the whole body. It is important to note that the cross-sectional area of the primary radiation beam is usually small and that the monitoring device may not indicate the maximum primary or stray radiation exposure to the operator.
11. Personnel monitoring (preferable finger or wrist devices) shall be required for all workers involved in the use of open beam X-ray equipment.
12. The personnel monitoring data shall be retained as a permanent record by the radiation protection supervisor and shall be available for examination by all personnel concerned.

Area monitoring

13. Radiation protection surveys should include monitoring for stray radiation in the immediate vicinity of the X-ray apparatus.

    Comment: These surveys, which may be performed by the operator or the radiation protection supervisor, may be necessary for the proper placement of shielding or for the location of barriers which limit the entry of persons into radiation controlled areas.

    Geiger-Mueller portable survey instruments may be valuable for locating stray radiation, although the results are not necessarily quantitative. If accurate exposure measurements are desired, the survey instrument should be calibrated with a source of low-energy X-rays. Consideration should also be given to possible monitoring errors due to the cross-sectional area of the monitored radiation beam being smaller than the sensitive area of the survey instrument. Defects in shielding may sometimes be best detected by means of films.

Safety engineering

14. The tube housing leakage radiation, measured at a distance of 5 cm from the surface of the tube housing with beam ports blocked, shall not exceed 25 mR in 1 hr, and should not exceed 0.5 mR in 1 hr at every specified tube rating.
15. Radiation originating within the high voltage power supply (i.e. transformer and rectifiers) shall not exceed 0.5 mR in 1 hr at every specified rating at a distance of 5 cm from the housing of the power supply.
16. For X-ray diffraction and spectrographic equipment in which the primary X-ray beam is completely enclosed, the stray radiation at a distance of 25 cm from the tube

housing-apparatus complex, as measured with a monitor appropriate for the energy range monitored, should be reduced to a minimal level and shall be less than 2 mR in 1 hr at every specified tube rating.

17. For open beam X-ray equipment the following precautions apply:
    (a) Either easily visible flashing lights or other equally conspicuous signals that operate only when the primary X-ray beam is released (i.e. X-ray tube activated and beam ports open) shall be provided in such a manner as to alert persons to the potential radiation hazard. This signal shall be labeled so that its purpose is easily identified.
    (b) The operator should be in immediate attendance at all times when the equipment is in operation. Deviations from this practice should be cleared through the radiation protection supervisor.
    (c) When not in operation, the equipment shall be secured in such a way as to be accessible to, or operable by, only authorized personnel.

    Comment: Because the exposure rate at the beam port may be greater than 100 000 R/min, extreme cautions are necessary to prevent accidental exposure to the primary beam. For this reason, open beam techniques should be used only after all other possibilities have been exhausted.
18. Each tube housing-apparatus complex should be so arranged as to prevent the entry of parts of the body into the primary radiation beam path or cause the primary radiation beam to be shut off upon entry into its path.
19. A shutter status (open or closed) indicator should be provided, on or adjacent to the tube housing, which will automatically indicate the position of each shutter, in a readily discernible manner.
20. A sign or label bearing the words 'Caution—Radiation—This Equipment Produces X-Radiation When Energized—To Be Operated Only By Qualified Personnel', or words having similar intent, shall be placed near any switch which energizes an X-ray tube. The sign or label shall use the conventional radiation caution colors (magenta on a yellow background) and shall bear the conventional radiation symbol.
21. A sign or label bearing the words 'Caution—High Intensity X-ray Beam', or words having similar intent, shall be placed on or adjacent to each X-ray tube housing. It should be located so as to be clearly visible to any person who may be working in close proximity to the primary radiation beam.
22. A red or magenta warning light with the notation 'X-Ray On', or equivalent, shall be located on the control panel and shall light only when the X-ray tube is activated. Also, a labeled X-ray tube status (on or off) indicator, preferably a red or magenta light, should be provided on or adjacent to each tube housing so that tube status is readily discernible.
23. Machines which utilize an X-ray diffraction camera should have appropriate ports of the X-ray tube housing arranged so that either:
    (a) The X-ray tube can be energized only when the camera collimating system is in place, or
    (b) A shutter mechanism allows the primary radiation beam to pass only when the camera collimating system is in place.
24. The coupling between the X-ray tube and the collimator of the diffractometer, camera, or other accessory shall prevent stray X-rays from escaping the coupling.
25. Safety interlocks shall not be used to de-activate the X-ray beam, except in an emergency or during testing of the interlock system. If the interlock system does turn off the X-ray beam, it shall not be possible to resume operation without resetting the beam 'ON' switch at the control panel.
26. All safety devices (interlocks, shutters, warning lights, etc.) shall be tested periodically to insure their proper operation. These tests should be conducted at least once per month. Records of such tests should be maintained.
27. All tube head ports which are not used shall be secured in the closed position in a manner which will prevent casual opening. Port covers shall offer the same degree of protection as is required of the tube housing (see Item 14).
28. Permanent shielding should be used in preference to temporary shielding.

    Comment: Lead foil should be used carefully, as it is easily distorted and may permit radiation leaks.
29. X-ray diffraction and spectrographic equipment should be placed in a room separate from other work areas, whenever possible.

Special requirements for research installations

30. Research projects may involve frequent modifications of the analytical X-ray equipment and there is often an associated increase in potential radiation hazards. Special efforts are necessary to control the hazards from such machines:
    (a) Radiation protection surveys should be made routinely and shall be made after each modification of apparatus.
    (b) Equipment operators shall wear radiation monitoring devices, preferably the finger or wrist type.

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Appendix A*

Maximum permissible dose equivalent values.

	Average weekly dose[a] (rem[c])	Maximum 13-week dose (rem[c])	Maximum yearly dose (rem[c])	Maximum accumulated dose[b] (rem[c])
Radiation controlled areas:				
Whole body, gonads, blood-forming organs, and lens of eye	0.1	3	–	5(N - 18)[d]
Skin of whole body	–	10	30	–
Hands and forearms, head neck, feet, and ankles	–	25	75	–
Environs:				
Any part of body	.01	–	0.5	–

[a]For design purposes only.
[b]When the previous occupational exposure history of an individual is not definitely known, it shall be assumed that he has already received the full dose permitted by the formula 5(N - 18).
[c]The dose equivalent in rems may be assumed to be equal to the exposure in roentgens.
[d]N = Age in years (must be greater than 18).

*From *Permissible Dose from External Sources of Ionizing Radiation*, National Bureau of Standards handbook 59 (1954) including 1958 Addendum and Statement by NCRP in *Radiology* **75** (1960).

Appendix B

Characteristic spectra for common analytical X-ray tube targets.

Target	Characteristic Wavelength Kα Angstrom	Kα keV	Kβ Angstrom	Kβ keV
Copper	1.54	8.01	1.39	8.92
Molybdenum	0.709	17.5	0.632	19.6
Iron	1.94	6.41	1.76	7.07
Tungsten	1.48[a]	8.40	1.28[b]	9.67
Chromium	2.29	5.42	2.08	5.94
Nickel	1.66	7.48	1.50	8.24
Cobalt	1.79	6.94	1.62	7.65
Silver	0.559	22.2	0.497	25.2

[a]Lα.
[b]Lβ.