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REQUIREMENTS FOR USE OF NONMEDICAL X-RAY GENERATORS AT SLAC*

Complied by

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PREFACE

The risks associated with use of x-ray equipment have long been recognized. While the relative frequency of x-ray damage is small, machine produced x-rays and large radiography sources continue to account for a large percentage of preventable radiation injuries reported worldwide.

The intent of this report is to formalize SLAC's radiation safety program as it applies to radiation producing equipment (diffraction, fluorescence analysis and nondestructive testing). It does not apply to the two-mile linac, experimental areas or other x-ray producing equipment directly related to the high energy physics program.

TABLE OF CONTENTS

GENERAL

This report is intended to outline controls on the acquisition and use of nonmedical radiation generators used at SLAC for analytical purposes and nondestructive testing.

It requires:

1. Registration and approval of all machines designed to produce x-rays for analytical or nondestructive testing including equipment built in-house.
2. Review of installations prior to routine use.
3. Radiation protection surveys and inspection.
4. Written operating procedures.
5. User authorization approval.

RESPONSIBILITIES

Operations Group Leader shall:

1. Notify the Group Leader for Operational Health Physics (OHP) prior to purchase or receiving x-ray generating equipment.
2. Notify OHP of any safety related equipment failure or proposed modification not previously reviewed.
3. Require the user to maintain a "USE" logbook documenting each time the HV is energized or changes in approved operations occur or routine maintenance.
4. Establish key control or other suitable safeguards to prevent unauthorized use.

5. Require the user to test door interlocks prior to each use and assure equipment inspection at least every six months and each time modifications are made to primary beam components or secondary shielding.
6. Require the availability and use of an approved radiation survey meter at least once during each use.
7. Assure that only authorized users of the equipment are issued keys to operate the equipment.
8. Prevent unattended operation without prior approval from OHP.

Operational Health Physics shall:

1. Review the proposed use of each x-ray generator and prescribe the necessary safeguards for routine use.
2. Provide radiation protection survey and periodic inspection at the users request and at least every six months.
3. Document user authorization approvals and specific operating procedures which shall be posted at each machine.
4. Provide radiation safety training as required.
5. Provide written x-ray generator authorizations (XGA) which shall be posted on each machine.

REFERENCES

1. SLAC Radiation Rule Book.
2. DOE order 5480.1A "Environmental Protection, Safety, and Health Protection Program for DOE Operations," Chapter XI, "Requirements for Radiation Protection."
3. NBS Handbook 114, "General Safety Standards for Installations Using Nonmedical X-Ray and Sealed Sources, Energies up to 10 MeV," ANSI N543–1974.
4. NBS Handbook 111, "Radiation Safety for X-Ray Diffraction and Fluorescence Analysis Equipment," ANSI N43.2–1977.

X–RAY GENERATOR AUTHORIZATION

An X-Ray Generator Authorization (XGA) shall be completed by OHP for each x-ray generator. This authorization shall include:

1. The name of the person or persons authorized by OHP to operate this equipment including the supervisor responsible for the area.
2. Any additional procedural or engineered safeguards required by OHP.
3. The location (building and room number) authorized by OHP.
4. Security requirements to prevent unauthorized use.
5. Classification of installation.

APPENDIX 1

Classification and Requirements of NBS 114

According to NBS 114, there are four recognized installation classifications. They are: Protective, Enclosed, Unattended and Open Installations. The most appropriate classification for SLAC is the enclosed type and must conform to the general and specific requirements appearing in Appendix 1. Open beam x-ray generators are prohibited without specific authorization of SLAC's Radiation Safety Officer (RSO) and OHP.

1. The source and all objects exposed shall be within a permanent enclosure, within which no person is permitted to remain during irradiation.

2. Reliable safety interlocks shall be provided to prevent access to the enclosure during irradiation.

3. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, there shall be provided:

   Fail safe audible or visible warning signals (preferably of the rotating beacon type) within the enclosure which shall be actuated a minimum of 20 seconds before irradiation can be started, and the visible signal shall remain actuated during irradiation.

   The audible signal shall be of a frequency or capable of producing a sound pressure level such that it can be heard over background noise that may be present.

   Suitable means of exit, so that any person who accidentally may be shut in can leave the enclosure without delay.

4. The exposure at any accessible and occupied area 1 foot (30 cm) from the outside surface of the secondary enclosure does not exceed 2 mR in any 1 hour. For x-ray installations, this exposure limitation shall be met for any

x-ray tube to be used in the enclosures and operating at any specified mA and kV rating within the manufacturer's published recommendations. No beam limiting device or filter shall be used during these tests unless such devices and filters are permanently attached to the x-ray tubes or gamma exposure device and the unit cannot be operated without their use. The radiation source and beam direction shall be positioned and oriented so that the highest exposure rate will be encountered in the area under test provided that such positioning and orientation can be achieved in normal usage.

5. All posting requirements as required by OHP shall be met in addition to those given below.

6. The accessible area in which exposure exceeds 2 mR in any 1 hour shall have signs posted showing the radiation symbol and the words "Caution: Radiation Area."

7. All entrances to a radiation area shall have signs posted showing the radiation symbol and the words "Caution: Radiation Area."

8. All installations shall display suitable warning signs as given below:

   The interior of the exposure room shall be posted with a sign that operates in conjunction with the warning signals in paragraph 3. The sign shall contain the radiation symbol and the words "Danger: High Radiation Area." The interior of a cabinet installation shall be posted with a similar sign which shall be visible with the access door open.

   The entrance to the exposure room shall be posted with a sign containing the radiation symbol and the words "Caution: Radiation Area." Cabinet type installations housing x-ray equipment shall have a sign on the outside showing the radiation symbol and "Caution: X-Rays." Cabinet type installations having a radioactive source shall have a similar sign but with the words "Caution: Radioactive Material."

Radiation Protection Surveys and Inspections

9. *Survey of New Installations.* Before a new installation is placed in routine operation a radiation protection survey shall be made by OHP.

10. *Changes in Existing Installations.* A radiation protection resurvey or reevaluation by OHP shall be made when changes have been made in shielding, operation, equipment, or occupancy of adjacent areas, and these changes may have adversely affected radiation protection.

11. *Report of Radiation Protection Survey.* No existing installation shall be assumed to conform with the provisions of this standard unless a radiation protection survey has been made by OHP and a report of the survey has been placed on file at the installation.

12. *Elimination of Hazards.* The radiation hazards that may be found in the course of a survey shall be eliminated before the installation is used.

13. *Retention of Survey Reports.* Reports of all radiation protection surveys shall be retained together with a record of the action taken with respect to the recommendations they contain.

14. *Radiation Protection Survey Procedures.* A radiation protection survey shall include the following procedures:

    Installation Inspection. The installation shall be inspected to verify or determine the present and expected occupancy of the adjacent areas. Devices that have a bearing on radiation protection shall be inspected for proper operation. These include audible or visible warning signals, interlocks, delay switches, and mechanical or electrical devices which restrict positioning of the radiation source.

    Radiation Measurements. Radiation exposure shall be measured in all adjacent areas that can be occupied. The measurements shall be made under practical conditions of operation that will result in the greatest exposure at the point of interest. X-ray apparatus should be operated

at the maximum kilovoltage and at its maximum milliamperage for continuous operation at that voltage.

    Personnel Monitoring. OHP shall determine the adequacy of the personnel monitoring programs for all classes of installations.

15. *Contents of Radiation Protection Survey Report.* A report of a radiation protection survey shall include:

    Identification of the persons conducting the survey and the date of survey.

    Identification of the radiation source and installation by suitable means, e.g., serial number, room number, and building number or name.

    Identification of instrument used and date of last calibration.

    The identity and Rhm or activity in curies of a gamma source, including calibration date, or the potential and current at which an x-ray tube was operated during the test.

    A statement indicating the appropriate classification of the installation.

(The following shall be included when applicable.)

16. The location of the source and the orientation of the useful beam with relation to each exposure measurement.

17. Exposure rates in all adjacent occupied areas. The locations of the measurements shall be suitably identified; appropriate drawings or sketches may facilitate this identification.

18. A description of the existing mechanical and electrical limiting devices that restrict the orientation of the useful beam and the position of the source.

19. A statement of the restrictions, if any, that shall be placed on the weekly workload, degree of occupancy and the time that the useful beam may be directed at any shielding barrier.

20. If an installation is found not to comply with this procedure, action required to ensure compliance shall be stated; if a resurvey will be required, it should be so stated.

21. *Inspections.* All radiation shields, interlocking switches and other safety devices shall be inspected periodically and appropriately serviced as scheduled by OHP. The interval between inspections shall not exceed 12 months.

22. Defective shielding barriers shall be promptly repaired and the inspection shall be repeated to determine whether the original degree of protection has been restored. If there is doubt about the adequacy of the repair consult with OHP.

23. Inspection of protective devices is not a substitute for a radiation protection survey.

24. Records of inspection dates, findings, and corrective actions shall be kept on file.

Operating Procedures

Restrictions According to Classification.

25. Since the safe operation of an Enclosed Installation is based on the normal operating conditions specified in the applicable radiation protection survey report, the equipment shall be operated only within the indicated limits.

26. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, the operator shall make a physical check of the enclosure before commencing or resuming operation.

27. When the operating conditions have changed so that there is a probability that the exposure of any person may be increased, a radiation protection resurvey or evaluation shall be conducted. In case of doubt, OHP shall be consulted.

28. *Radiation Protection Responsibility.* A competent person shall be designated as the Radiation Protection Supervisor usually the operations group leader. This person shall be qualified by training or experience to carry out his duties as indicated below:

    Insuring that all installations are operated within the limitations of the appropriate radiation protection survey reports.

    Instructing personnel in safe working practices and the nature of injuries resulting from overexposure to radiation.

    Report to OHP any incident of abnormal exposure or suspected overexposure of personnel to determine the cause and take remedial action.

    Assuring that interlock switches, warning signals and signs are functioning and located where required.

29. *Radiation Safety Instructions.* Radiation safety instructions shall be posted and furnished to each radiation worker in writing.

Personnel Monitoring

30. Personnel monitoring shall be required for all workers involved in the use of radiation apparatus. Film badges or thermoluminescent dosimeters are acceptable for this purpose.

31. Personnel monitoring shall be performed in controlled areas for each occupationally exposed individual for whom there is a reasonable possibility of receiving a dose in any calendar quarter exceeding 10% the applicable quarterly dose equivalent (see Appendix 5).

32. Records shall be kept concerning worker radiation exposures. These records shall include, as appropriate, results from individual film badges, pocket dosimeters or chambers and calculated results.

Radiation Measurement and Instrument Calibration

33. Sufficient and suitable radiation survey instruments shall be available to properly support the use of radiation sources. The instruments shall be capable of detecting and measuring the types and levels of radiation involved.

34. Each radiation survey instrument shall be calibrated at intervals not to exceed three months, and after each servicing and repair.

APPENDIX 2

Simple Methods for Estimating X-Ray Intensity from Analytical Tubes

There are many different experimental configurations and x-ray tube designs that will affect exposure rates from analytical x-ray equipment. The following methods are useful for approximating potential exposure rates. They should be used with caution. Accurate measurements in the primary and scattered beam must be made to determine intensity more accurately.

Radiation surveys of analytical x-ray generators must be performed with great care. Both scattered and primary beams are usually small in area and the detector area is large resulting in exposing only a small portion of the sensitive volume. To determine the true exposure rate the beam area must be known or at least approximated. This correction is proportional to the ratio of the detector area to the beam area multiplied by the observed exposure rate. For example, if the scattered beam intensity measures 100 mR/h with a 9 cm diameter thin window ionization chamber and a polaroid film reveals a 1 cm diameter beam, what is the true exposure rate?

$$
\begin{aligned}
\text{Beam Area} &= 0.79\ \text{cm}^2 \\
\text{Detector Area} &= 64\ \text{cm}^2 \\
\text{Exposure Rate} &= 100\ \text{mR/h} \\
x &= \text{Detector Area/Beam Area} \cdot \text{mR/h} \\
&= 64/0.79 \cdot 100\ \text{mR/h} = 8100\ \text{mR/h}
\end{aligned}
$$

To avoid this error, one can measure the exposure rate at a greater distance where the cross sectional area of the beam is larger than the chamber. This is seldom possible with analytical equipment due to tight geometry. In actual practice the scattered beam is easily shielded with thin layers of Pb foil or an interlocked secondary enclosure. Scattered x-ray beams are usually shielded so that there is no detectable exposure rate.

Production of X-Ray

The production of x-rays is a function of applied voltage, tube current and target material. The x-ray intensity is proportional to the voltage squared $(kV)^2$, tube current (mA) and atomic number of the target (Z). In most x-ray tubes the target is tungsten and cannot be altered by the user. However, this is not the case for fluorescence and diffraction equipment. The user can alter the x-ray intensity by increasing or decreasing the applied voltage and tube current and by changing the target material.

Target Material

The fraction of accelerated electron energy given up as x-rays can be estimated by:

$$F = VZ \times 10^{-6}$$
$$V = \text{Applied tube voltage, kV}$$
$$Z = \text{Target atomic number}$$

For a tube with a tungsten target operating at 40 kV less than 0.3% of the total electron energy appears as x-rays. This expression holds reasonably well for potentials up to a few MV.

Estimation of Primary Beam Intensity

To determine exposure rates at fixed distances from the x-ray target use Figures 1 and 2. Caution should be exercised because these values are typical and are dependent on tube design and other factors. The true exposure rate must be measured!

For example, consider a thin *Be* window x-ray tube operating at 50 kV constant potential and 20 mA. Approximate the exposure rate at 10 cm from the target (~ 8 cm from the exit window).

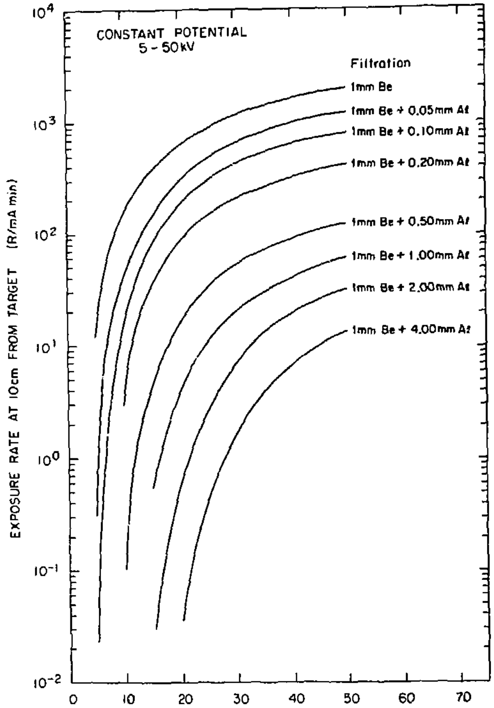

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Figure 1. "Handbook of Radiological Protection," London: Her Majesty's Stationary Office, 1971.

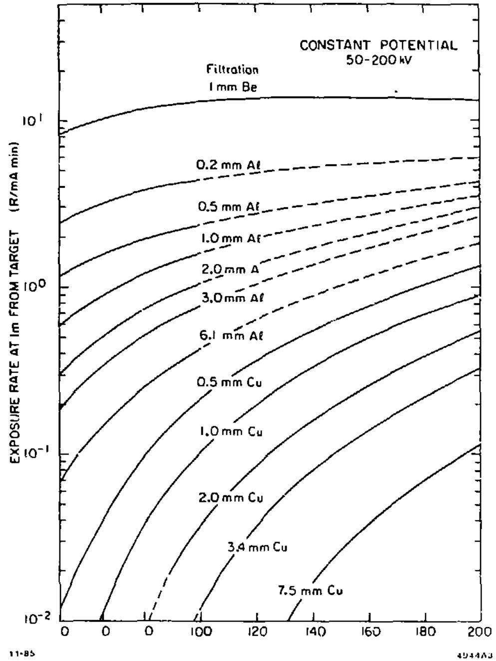

Figure 2. "Handbook of Radiological Protection," London: Her Majesty's Stationary Office, 1971.

$$
\begin{aligned}
x\ (\mathrm{R/min}) &= (\mathrm{R/mA\text{-}min})(\mathrm{mA}) \\
&= (2 \times 10^3)(20) \\
&= 4 \times 10^4\ \mathrm{R/min} \\
&= 2.4 \times 10^6\ \mathrm{R/h}
\end{aligned}
$$

Another simple method developed by Lindell* for estimating exposure rates, is claimed to be accurate to within a factor of 2:

$$x\ (\mathrm{R/sec}) = 50 \cdot \frac{(\mathrm{kV})(\mathrm{mA})}{\mathrm{cm}^2} \cdot \frac{Z}{74}$$

Using the first example and Lindell's expression, determine the exposure rate in the primary beam for a tungsten target ($Z = 74$).

$$
\begin{aligned}
x &= 50 \cdot \frac{(50)(20)}{(10\ \mathrm{cm})^2} \cdot \frac{74}{74} \\
&= 500\ \mathrm{R/sec} \\
&= 3 \times 10^4\ \mathrm{R/min} \\
&= 1.8 \times 10^6\ \mathrm{R/h}
\end{aligned}
$$

It must be remembered that these methods only estimate the exposure rate. However, they are sufficiently accurate for planning and training purposes. See Table I for comparison of two methods.

Estimation of Scatter Exposure Rates

This approximation is more complex and can best be illustrated by using actual measurements. Using the technical factors in the previous example, Howley

* "Occupational Hazards in X-Ray Analytical Work" by Bo Lindell, Health Physics 15, 481-486 (1968).

Table I
Comparison Between Graph and Lindell's Formula
at 10 cm and 20 mA

	Graph		Lindell	Ratio
kVp	R/mA-min	R/min × 10^4	R/min × 10^4	G/L
10	140	0.28	0.6	0.47
20	540	1.1	1.2	0.92
30	1200	2.4	1.8	1.3
40	1700	3.4	2.4	1.4
50	2000	4.0	3.0	1.3
60	2300	4.6	3.6	1.3
70	2600	5.2	4.2	1.2
80	2900	5.8	4.8	1.2

and Robbins† measured the primary and secondary exposure rates from a typical x-ray diffraction unit (Figure 3). While these values may differ because of geometry, experimental apparatus and other factors, they illustrate the magnitude of potential exposure. Note that the scatter exposure rate increases from near 0°-180° while the primary beam exposure rate decreases with increasing distance from the tube at 0°. This example is very geometry dependent and should not be used for design purposes.

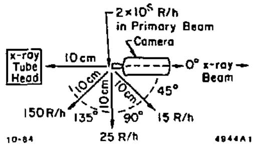

Figure 3

† "Radiation Hazards from X-Ray Diffraction Equipment" by J.R. Howley and C. Robbins, Radiological Health Data Reports 8, No. 5, 243-300 (1967).

APPENDIX 3

Biological Effects of High Dose Ionizing Radiation

The accidental exposure of living tissue to very high doses of ionizing radiation produces injuries that are very similar to thermal burns. For analytical x-ray generators, the most probable areas exposed are the hands, fingers and facial area including eyes.

There are basically two general types of injuries: acute and chronic. Acute injury, depending on the dose, will occur within a few hours to months following the exposure. Chronic injury may occur many years later and includes cancer induction at the injury site or cataract induction if the eyes are involved.

Acute injury of the skin has been classified into the following types* :

Type I. Skin reddening, very much like a sunburn and equivalent to a first degree thermal burn. Acute doses of a few hundred rad can cause delayed symptoms.

Type II. Wet scaling is equivalent to a second degree thermal burn. Following the skin reddening, blisters form and break open leaving the tissue raw and painful. Acute doses of 1000-2000 rad can cause this condition.

Type III. Following the appearance of *Type I* and *Type II* symptoms radiation-induced skin death is caused by acute radiation doses in excess of 2000 rad. These lesions resemble those caused by severe scalding or chemical burns and follow the course of third degree burns requiring surgical excision or amputation of dead tissue.

* "Clinical Course and Dosimetry of Acute Hand Injuries to Industrial Radiographers from Multicurie Sealed Gamma Sources," Saenger et al., The Medical Basis of Radiation Accidents (Elsevier/North-Holland).

Type IV. For continuous exposure to high radiation doses lower than the threshold for acute injury, an eczema-like condition may occur. This may happen for life-time exposures (30+ years) and requires several thousand rad exposure during this period or about 1 rad/d for 30 years. Skin cancer occurs in a large (but unknown) proportion of cases exhibiting chronic radiation dermatitis.

APPENDIX 4

Special Procedure for Shielded Room Radiography

Introduction

This procedure establishes special radiation safety requirements for the use of radioactive sources or radiation-producing machines to perform radiography in shielded enclosures at SLAC. Radiography means "the examination of the physical structure of materials, other than human beings or animals, by nondestructive methods using ionizing radiation."

Control of Equipment and Security

The radioactive exposure device is also the storage container for the radioactive source. The amount of radioactivity in the device with the sealed source in the shielded or "off" position, shall be limited so that the dose rate at any accessible surface will be less than 200 mRem/h and at 1 meter less than 10 mRem/h.

Each exposure/storage device shall have a lock designed to prevent unauthorized or accidental exposure and shall be kept locked at all times except during use. The key shall be controlled by the radiographer. The radiographer shall be present at all times when the exposure device is or could be turned "on" or with the specific approval of OHP.

The radiography source shall be used only in an interlocked shielded room approved by OHP. The in-cell radiation monitor and the audible/visual alarm shall be active and tested at the beginning of each radiography session by the radiographer.

Replacement, modification and leak testing of the radiography source shall be performed by persons specifically authorized by OHP. Routine leak testing shall be performed at least every six months. Contamination and leak tests shall be capable of detecting 0.005 uCi.

The radiographer shall be provided with a SLAC personnel monitor and in addition a pocket ionization chamber (PIC). The operator will note before and after readings in the utilization log book. It is the operator's responsibility to notify OHP if the integrated dose in any single radiography session exceeds 20 mRem.

Shielded Room

The shielded enclosure shall be inspected by OHP at least once each year. It is the responsibility of the radiographer to notify OHP of any changes that might compromise the shielding integrity, interlocks or controlled access. The radiographer shall search the enclosure prior to opening the shutter to assure that no one is left in the room. The interlocks shall not be defeated for any reason without the approval of OHP. If such a procedure is necessary a prominent warning to the effect must be displayed at the control panel. The room entrance shall be kept locked at all times when unattended.

Utilization Log

The radiographer shall maintain the utilization log. All relevant safety information shall be recorded. Each time the source is "on" the radiographer shall record the date and time of each session along with the total time that the source was exposed. All failures of the interlock system, radiation warning system or warning lights on the control panel shall be noted. OHP shall be notified as soon as any failure of the above is discovered.

The attached checklist can be pasted into the log once completed by the radiographer.

Operator Training

This procedure applies only to shielded room radiography. Extensive lecture training is therefore not necessary. All training will be by on-the-job-training

methods. It is necessary that the radiographer demonstrate a thorough knowledge of operating and safety procedures related to radiation protection. The radiographer using this equipment shall be approved by OHP following an observation period demonstrating satisfactory performance.

RADIOGRAPHY CHECKLIST

Date : ______________

Time : Begin ______________ End ______________

Safety Systems : Shutter Lights yes ____ no ____

Access Door yes ____ no ____

Radiation Monitor yes ____ no ____

Radiography : Device __________ Number of Views __________

Exposure time ____________ per view

Distance ____________ cm

PIC : Begin ______ End ______ Dose __________ mR

Signature: ______________________________

APPENDIX 5

Radiation Protection Standards for External Ionizing Radiation Exposure

A. Occupationally Related Exposure of Individuals in Controlled Areas

Radiation exposures shall be limited to levels reasonably achievable within the standards prescribed below.

Type of Exposure	Exposure Period	Dose Equivalent (rem)
Whole body, head and trunk, gonads, lens of the eye, red bone marrow, active ! ood-forming organs.	Year Calendar Quarter	5 (notes 1,3) 3
Unlimited areas of the skin (except hands and forearms). Other organs, tissues, and organ systems (except bone).	Year Calendar Quarter	15 5
Bone	Year Calendar Quarter	30 10
Forearms (note 2)	Year Calendar Quarter	30 10
Hands and feet (note 2)	Year Calendar Quarter	75 25

1. In special cases, with the approval of EP-30, a worker may exceed 5 rem/year, provided his or her average exposure per year since age 18 will not exceed 5 rem per year. This does not apply to emergency situations.
2. All reasonable effort shall be made to keep exposures of forearms and hands to the general limit for the skin.
3. SLAC Guideline is 1500 mrem/year.

B. Exposure of Individuals and Population Groups in Uncontrolled Areas

Exposures to members of the public shall be as low as reasonably achievable levels within the standards prescribed below.

Type of Exposure	Annual Dose Equivalent or Dose Commitment (rem)	
	Based on dose to individual at points of maximum probable exposure (rem)	Based on average dose to a suitable sample of the exposed population (rem)
Whole body, gonads, or bone marrow	0.5	0.17
Other organs	1.5	0.5