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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/05/2004	00	New technical basis document for the Portsmouth Gaseous Diffusion Plant – Occupational Medical Dose. First approved issue. Initiated by Mark Notich.
07/19/2004	01	Incorporates comments from internal and NIOSH formal reviews. Approved Issue of Revision 01. Initiated by Mark Notich.
07/07/2006	02	Deletes the uterus as an analogue/surrogate organ in Table 3-10 on page 16 in Section 3.4.5 as per Task 5 comment. Updates required introductory language on pages 6 and 7 in Section 3.1. Revised to change from a page change (Rev 01 PC-1-B) to a revision (Rev 02-A) as a result of NIOSH comment. Added a Purpose and Scope subsection to the Introduction (Section 3.1). Approved issue of Revision 02. This revision results in a reduction in assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Paul J. Demopoulos.

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ACRONYMS AND ABBREVIATIONS

A/P	Anterior Posterior (x-ray view)
AAPM	American Association of Physicists in Medicine
Al	Aluminum (x-ray machine filtration)
DEP	Ohio State Department of Environmental Protection
DOE	U.S. Department of Energy
ESE	Entrance Skin Exposure
ESEG	Entrance Skin Exposure Guideline
FDA/BRH	Food and Drug Administration Bureau of Radiological Health
GAT	Goodyear Atomic Corporation Technical Report
HVL	Half Value Layer
ICRP	International Commission of Radiation Protection
IREP	Interagency Radiation Exposure Program
kVp	Kilovolts Peak or peak kilovoltage
LAT	Lateral (x-ray view)
mA	Milliampere
mAs	Milliampere seconds
mR	MilliRoentgen
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
P/A	Posterior Anterior (x-ray view)
PORTS	Portsmouth Gaseous Diffusion Plant
QA	Quality Assurance
RMS	root mean square
SID	Source to Image Distance
SSD	Source to Skin Distance
TBD	Technical Basis Document

3.1 INTRODUCTION AND OCCUPATIONAL MEDICAL DOSE

The Portsmouth Gaseous Diffusion Plant (PORTS) required pre-employment physical examinations as part of their occupational health and safety program. These medical examinations typically included diagnostic chest x-rays. Medical x-rays during employment are offered every three years since 1989 but are not mandatory. The doses from these diagnostic x-ray procedures depended not only on the characteristics of the x-ray machine and the procedure used, but also on the frequency of the examination. Other types of x-rays such as lumbar, knee or ankle x-rays were given for on the job injuries at the discretion of the medical director but are not included in doses under EEOICPA.

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located…in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations…pertaining to the Naval Nuclear Propulsion Program)" [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer…was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c)…" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at the facility in its dose reconstructions for employees at DOE facilities, including radiation

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures.
- Radiation from diagnostic X-rays received in the treatment of work-related injuries.

3.1.1 Purpose

The purpose of this TBD is to describe the occupational X-ray program for the PORTS plant. This document discusses historical and current practices in relation to the evaluation of X-ray external exposure data for PORTS workers.

3.1.2 Scope

This TBD contains supporting documentation to assist in the evaluation of occupational external X-ray doses from medical evaluations of workers at PORTS. An objective of this document is to provide supporting technical medical X-ray equipment data or survey information to evaluate, with claimant favorable assumptions for workers evaluated for work related reasons.

3.2 EXAMINATION FREQUENCIES

X-ray examinations were conducted consistently for employees every three years from 1989 to present. Included in the medical procedures is the frequency of chest x-rays that were offered based upon worker age. Note asbestos and beryllium workers were required to have annual x-rays. After the pre-employment physical examination, chest x-rays were optional. This information may be recorded in the worker file provided by the U.S. Department of Energy (DOE). All occupational x-rays in the worker file are to be included in the reconstruction of occupational dose.

Table 3-1 lists the frequencies of chest x-rays for different age groups through the years and also identifies specific groups of workers. Declared pregnant women were not x-rayed from at least 1989. Typically one Posterior/Anterior (P/A) view was taken but Anterior/Posterior (A/P) and Lateral (LAT) view(s) were possible.

Table 3-1. Frequency of occupational chest X-rays at the PORTS.

Period	Frequency	Comment
1954–1989[a]	Annually	All employees.
	Annually	Asbestos/beryllium workers.
1990–2003	Offered every 10 years	Employees up to 30 years old.
	Offered every 5 years	Employees up to and equal to 45 years old.
	Offered every 3 years	Employees greater than 45 years old.
	Annually	Asbestos/beryllium workers.

PORTS medical records include notations in individual worker files regarding both the date and the purpose of the of x-ray examinations. Included in some of the more recent records is the number of views. The current Medical X-ray technician stated the number of re-takes was virtually none. This is because the employees had shown concern about how many x-rays they were given, (1993 – present). The complex-wide x-ray guidance Technical Basis Document (TBD) indicate a 3 % re-take rate based upon Trout et al (1973) in their analysis of the rejection rate of chest radiographs obtained

during the Coal Mine "Black Lung" program reported an average rejection rate of 3% among 67,000 radiographs. International Commission of Radiation Protection (ICRP) Publication-34 (ICRP-34) indicates a minimal value of 10 –12 % re-takes (ICRP 34, p 37). A 5 % re-take value will be used to be claimant favorable.

Retakes should serve as a signal to give special consideration to the evaluation of technique factors, and hence the resultant dose calculations. A retake in a very large individual might serve as a signal that the initial radiograph was taken with technique factor settings suitable for a smaller person, and that the second radiograph reflected an additional and larger dose.

About 80 % of the x-rays given were P/A chest x-rays. The others comprised of knee, hand, ankle legs and others mostly for injuries sustained at work.

Specific organ doses to be attributed for P/A chest x-rays calculated on the basis of the dose conversion factors found in ICRP Publication 34 are given in Attachment A, Table A-1and A-2. LAT dose conversion factors are given in Attachment A, Table A-3 and A-4. For organs not listed in ICRP Publication 34 but specified in the Interagency Radiation Exposure Program (IREP) code, doses were determined by analogy with anatomical location (Table 3-9). Thus IREP code organs in the thoracic cavity, but not mentioned in the ICRP Publication 34 were assigned the same dose as the lungs; doses to the organs in the head and neck were assigned the same dose as the thyroid. The head and neck organ dose estimates (i.e. eye/brain), should be somewhat greater than doses actually incurred (hence claimant favorable), because of geometry considerations and at least in the case of the brain, because of attenuation by the bony cranium. To ensure claimant favorability in the view of the variations in organ dose described in ICRP Publication 34 (p. 51), the doses for females (lungs), which are slightly higher than those for males, were used.

3.3 EQUIPMENT AND TECHNIQUES

3.3.1 Photofluorography

Chest photofluorography, which resulted in very much greater patient doses from a diagnostic procedure, was used sporadically until as late as the early 1960's. Photofluorography used a smaller film (4 x 5 inches), a smaller source to skin distance (SSD) (42 inches), and both a higher peak kilovoltage (kVp) and typically a several fold greater exposure in terms of milliampere seconds (mAs). Exposure was regulated by photometers, which utilized the exposure to the film to determine the time of exposure.

Even-though no evidence of the use of photofluorography was found at PORTS it is reasonable to presume that at least some of the occupational medical diagnostic chest x-rays with the DOE and its predecessor organizations were accomplished by photofluorography. The use of photofluorography should be assumed to ensure claimant favorable dose reconstructions from the time-period of 1954 through 1960.

Photofluorography differed from conventional radiography with film in that while kVp and milliampere (mA) settings could be manipulated by the technician, the exposure time was regulated by the amount of light generated in the photofluorographic unit, with a cutoff or maximum exposure time. An exposure of 15 mAs (150 mA for 0.1 second) was sufficient to produce a satisfactory image on 35 mm film (four by five inches); larger film required greater exposures (Sante 1954, p. 129).

Typical operating parameters reported for 1950's photofluorography were 24 mAs at 83 kVp at a target to film distance of 36 inches (Braestrup 1958, p. 143), and 30 mAs at 90 kVp with a target to

film distance of 40 inches and 2.4 mm added filtration. In the absence of data, a HVL of 2.5 mm should be assumed for dose determinations and is claimant favorable. Measurements at the Hanford site indicated that for a 60 mAs photofluorography exposure at 100 kVp, the entrance skin exposure (ESE) was 1.53 R (Rising and Soldat 1959), which is likely an upper limit value based on a large patient and is consistent with an ESE of about 600-700 milliroentgen (mR) for a 24-30 mAs exposure at somewhat lower kVp. The Hanford measured value of 1.53R ESE is likely an upper limit and hence an overstatement of the actual exposure from photofluorography to the average patient, and thus this 1.53R ESE value should be used in the absence of data to ensure claimant favorability.

3.3.2 Pre-1970

The x-ray machine information prior to 1970 is not available. The ESE was based upon the complex-wide x-ray TBD guidance as presented in Table 3-8. Default Dose Values by Procedure presented in section 3.3-1. An air kerma of 200 mR for P/A and 500 mR for Lat x-rays was utilized in the organ dose calculations.

3.3.3 Type I (1970-1978)

The x-ray machine information from 1970 - 1978 is not available. The ESE was based upon the complex-wide x-ray TBD guidance as presented in Table 3-8. Default Dose Values by Procedure presented in section 3.3.1. An air kerma of 100 mR for P/A and 250 mR for Lat x-rays was utilized in the organ dose calculations.

3.3.4 Type II - III

The imaging system and generator have been the only changes since 1979. Currently in use is a GE MVP Micro x-ray 60 with a model COLL-C-150 x-ray tube. It can operate up to 150 kVp in a single-phase mode and up to 320 mA. ESE measurements do exist in some cases from the Ohio State Department of Environmental Protection (DEP), the Federal Drug Administration Bureau of Radiological Health (FDA/BRH) currently the Center for Devices and Radiological Health, and the Health Physics group at PORTS. However it is more claimant favorable to utilize the ESE values as calculated from the technique factors.

Records concerning the medical x-ray equipment at PORTS from 1954 to 1979 were not located. A conversation with a physician that worked at the PORTS medical center within this time frame indicated that the employees went to three area hospitals for x-rays including the Southern Ohio Medical center during this time period for annual chest x-rays (Dr. Spears, conversation 9/18/03).

A summary description of the x-ray equipment used at PORTS is included in Table 3-2. A summary of the specific technique factors for these machines is presented in Table 3-3.

Table 3-2. Description of the X-ray equipment used at PORTS.

Technique	Period	Equipment
Photofluorography (PF)	1954-1960	No information available.
Pre-1970	1961-1969	No information available.
Type I	1970–1978	No information available.
Type II	1979-1991	Hi-Speed Rare Earth Screens, Kodak X DMAT Model M-7B film Processor, GE MVP Micro x-ray 60 x-ray generator , GE Col C-150 x-ray Tube, Stationary 12:1 Grid, Film Processor, Manual timer, Manual techniques
Type III	1992–present	Hi-Speed Rare Earth Screens, Kodak X DMAT Model M-7B film Processor, GE MVP Micro x-ray 60 x-ray generator , GE Col C-150 x-ray Tube (same as type II above), Stationary 12:1 Grid, Film Processor, Automatic timer, Phototimed exposures

Table 3-3. Technique factors used for each type of X-ray equipment.

Machine	View	Current (mA)	Voltage (kVp)	Exposure time (sec.)
Type I	Techniques unknown. No records were kept with regard to the technique factors used during this time period.			
Type II[b]	P/A[a]	200	110	1/10
Type III[b]	P/A	200	110	1/10

a. P/A indicates a P/A view, the average P/A chest measures 26 cm. The average Lat. chest measures 34 cm.
b. Manual technique factors obtained from PORTS medical x-ray technologist.

Since no technique factors were identified by PORTS for Type I equipment, organ doses based on assumed technique factors were developed on the basis of x-ray techniques contemporary with the time period (i.e. 1970-1978) with due consideration given to claimant favorability. Accordingly, it was assumed that the operating kVp was 80, somewhat higher (and hence claimant favorable) than the kVp values typically used at the time (Morgan and Carrigan, 1955; Laughlin et. al. 1957). To offset this lower kVp, an increased exposure would be required as compared with Type II exposures, and this was conservatively taken to be 30 mAs, based on exposure time of 0.1 second at 300 mA. External filtration was assumed to be 1.5 mm Aluminum (Al) as compared with 2.5 mm Al used subsequent to 1979, which would further increase the dose. The SSD was assumed to be 152cm based on a Source to Image Distance (SID) of 183cm less a chest thickness of 26cm and an addition of 5cm to account for cassette thickness. {The Hanford TBD indicates a 79 mR ESE or 4 mR/mAs value for earlier era x-rays.} (ORAUT-TKBS-0003 TBD, 2003 and ORAUT-TKBS-0006-3 TBD 2003)

Some measurement results follow. As can be seen it would be more claimant favorable to utilize technique factor information for all x-ray machines. One result for ESE (PORTS HP department measurement) at a SID of 178 cm, 124 kVp, 250 mA, 0.013 sec yielded 6.0 mR exposure or 1.84 mR/mAs. (PORTS HP x-ray Quality Assurance (QA) survey, 1994) A second result for ESE (FDA 8/24/92 measurement) at a SID of 178 cm, 23 cm chest LucAl phantom, 120 kVp, 200 mA, and 0.1 sec yielded a 12.8 mR exposure or a 0.64 mR/mAs. A third result for ESE (FDA 8/24/92) at a SID of 178 cm, 23 cm chest LucAl phantom at 110 kVp, 320 mA, 0.083 sec yielded a 16.7 mR exposure or 0.62mR/mAs.

The x-ray equipment currently in use has been QA checked for entrance skin exposure (ESE) by the manufacturer since 1979 and from the Health Physics group since 1985. Although all of the records for these QA checks on the x-ray equipment could not be found, the records available indicate that the x-ray equipment was working within FDA guidelines. American Association of Physicists in Medicine (AAPM) report number 4, “Basic Quality Control in Diagnostic Radiology” (1978), was followed to ensure Entrance Skin Exposure Guide (ESEG) was achieved. A diagnostic medical x-ray survey checking ESEG for different projection limits was followed. The QA of the x-ray machine included checks on the kVp, half value layer (HVL) determination for beam quality, exposure timing accuracy, beam collimation and alignment testing, and film-screen contact testing. Table 3-4 through Table 3-6 summarizes the parameters tested and the allowed tolerances as stated in the PORTS procedure (Bassett 1985).

Table 3-4. Medical x-ray quality assurance parameters/PORTS.

kVp requirements	+/- 4 kVp (about 4%)
Timing requirements	t +/- 5 % for t > 10 msec and t +/- 20 % for t < 10 msec +/- 10% is used at PORTS no matter what the time.
Beam alignment, light and radiation field congruence requirements	less than 2% of the source to image distance (SID) or 2 cm.

The limits for HVL are as follows:

Table 3-5. Half value layer limits .

Measured kVp	Minimum HVL (mm Al)
50	1.3
60	1.3
70	1.5
80	2.3
90	2.5
100	2.7
110	3.0
120	3.2
130	3.5
140	3.8
150	4.1

Source: Bassett 1985, "Medical x-ray Quality Assurance Tests," p 4

The ESE limits are as follows:

Table 3-6. Entrance skin exposure limits.

Projection	ESEG (mR)
Chest (P/A)	30
Skull (Lat)	300
Abdomen (A/P)	750
Cervical Spine (A/P)	250
Thoracic Spine (A/P)	900
Full Spine (A/P)	300
Lumbo-Sacral Spine (A/P)	1,000
Retrograde Pyelogram (A/P)	900
Feet (D/P)	270

Source: Bassett 1985, "Medical x-ray Quality Assurance Tests," p 6

From 1979 to 1994 a manual technique setting of 0.1 sec at 200 mA and 110 kVp was utilized for chest P/A views. (Communication with medical x-ray technologist.) After 1994 the exposures were photo-timed. To be more claimant favorable the manual techniques are utilized for Type I through Type III machines.

X-ray organ dose estimates for occupational x-rays administered at PORTS are made for Type I equipment (used from 1970 through 1978), Type II equipment (used from 1979 to 1991), and Type III equipment (used from 1992 to the present).

For the posterior/anterior view (P/A), a standard SID of 72 inches (183 cm) was used. Additional information indicated that all of the x-ray machines were single phase and that there was no air gap between the patient and the film. QA checks of the Type II and III machine indicated a 3.3 mm Al HVL. A value of 3.5 mm Al HVL would be claimant favorable for types II - III. Tables A-1 and A-2 list organ doses for P/A 14" x 17" chest films.

For the LAT, 2.5 times the P/A entrance kerma value was used to estimate the LAT entrance kerma value. Tables A-3 and A-4 list organ doses for LAT 14" x 17" chest films.

3.3.5 Diagnostic X-Ray Technique Generalizations 1954 to Date

For convenience and possible application to cases in which the standard PORTS protocol was not followed, or for generic use, the effect of various technical factors has been tabulated below in Table 3-7.

Air kerma was corrected for the thickness of the chest (26 cm) and for distance between the chest and the plane of the film (5 cm) to obtain the air kerma at skin entrance. The higher 3.5 mm Al filtration value was used since the dose conversion factors would be higher for 3.5 mm compared to lower values and thus more conservative and claimant favorable.

Table 3-7. Relationship of beam intensity and various technical factors.

Parameter	Units	Relationship with intensity
Applied voltage	kVp	Intensity proportional to 1.7 power of kVp
Tube current	mA	Linear
Exposure time	s	Linear
Filtration	mm Al	Intensity decreases by ~40% for each additional mm Al
Patient size (chest thickness)	25-27 mm >27 mm	Dose increased by factor of 1.5 Dose increased by factor of 2
Distance	d	Approximately inverse square relations ($1/d^2$)
Uncertainty	+30%	Assume all errors are positive, + 30% should be used
Re-takes	+5%	Assume all workers had re-takes equal to 5% average

Source: ORAUT-TKBS-0006-3 TBD 2003, p6

3.3.5.1 Collimation

Collimation refers to the size of beam. Early, the philosophy was to use a fairly large aperture (i.e. limited collimation) to ensure that the entire area of interest was included in the radiograph. Subsequently, because of patient protection concerns, beams were collimated such that the smallest beam consistent with the area of interest was used, thereby limiting the area of the patient exposed, and, in the case of chest radiography, minimizing dose to organs such as gonads, thyroid, and gastrointestinal tract. Wochos et al. (1979) analyzed the 1972-1975 Nationwide Evaluation of X-Ray Trends (NEXT) data and found that at some facilities, primarily Internal Medicine and Medical GPs, the beam area to film area ratio could be as high as 2.0.

In early years of operation (pre-1970), x-ray beam or scatter measurement data, techniques, or beam port information may not be available to estimate the collimation of the x-ray beam. Feldman et al. (1957) noted wide variation in their review of x-ray dose literature in 1957. Through measurements, Feldman et al. (1957) noted a factor of 10 increase in the gonadal dose when no external collimation was used.

Due to the reported variation in the literature and measurement data on the effects of collimation, the claimant favorable assumption of no external collimation of the primary beam should be used when measurement data, technique, or other information to describe the collimation are not available for x-rays taken prior to 1970. This is based on the following claimant favorable assumptions and professional judgment:

In the late 1950s, there was significant research into the gonadal dose and the reasons for the observed variation in dose. This research described the effects of filtration, collimation, and centering. By the early 1960s, techniques were being modified incorporating additional collimation. While these techniques were likely fully incorporated at most DOE facilities by 1965, to allow for the possibility that

some smaller facilities might not have had the resources to update their equipment and to be claimant favorable, the year 1970 was selected.

In 1968, the National Council on Radiation Protection and Measurements (NCRP) in Report 33 updated their guidance on medical x-ray protection. While many DOE facilities had probably already incorporated the guidance in this report, some smaller facilities might not have incorporated the guidance by 1968. To ensure that these facilities were in fact in conformance with the 1968 recommendations, an additional two-year period was added.

By the late 1950s, reports in the literature of most of the surveys of medical x-ray facilities revealed low gonadal doses, indicating adequate collimation. A few surveys clearly indicated the use of collimation was limited. Of the eight surveyed facilities at Oak Ridge, only one (13%) had a moderately high male gonadal dose (5 mrad). All of the other facilities, the male gonadal dose was less than 2 mrad. Variation between the other facilities appeared to be the result of differences in the use of filtration and cone size. Since most facilities were using some form of collimation by the late 1950s, by the mid 1960s most, if not all, facilities were probably using some form of collimation.

Since references as to when all facilities were using adequate collimation were not found, professional judgment was used to estimate this time-period to be the mid 1960s. *To fully assure claimant favorability, this assumption has been further expanded by 5 years to 1970 to allow for the uncertainty in professional judgment.* (ORAUT-OTIB-0006, section 2.4)

Review of the available documentation pertaining to the occupational medical program at PORTS from 1954 to the present revealed that only one diagnostic medical radiographic procedure was administered in connection with pre-employment or regular post-employment medical examinations, Posterior-anterior (P/A) 14” x 17” chest film. The LAT chest film was included in case records indicate their usage. Accordingly, only doses from these two techniques were evaluated. Any other radiographic examinations of PORTS employees that might have occurred were non-occupational in the sense that these were necessitated by illness or injury and hence not a part of the employee physical examination process. Thus, there is no indication in the records that other diagnostic radiographic examinations were administered as a part of the occupational medical program.

3.4 ORGAN DOSE CALCULATIONS

ICRP Publication 34 (1982) provides tables of average absorbed dose (mGy) in selected organs for selected x-ray projections at 1 Gy entrance kerma (i.e., air kerma without backscatter), for selected views (including P/A), and for selected beam qualities (i.e., various HVLs). These tables provide the basic dose conversion factors for converting air kerma to organ dose. The average air kerma rates for the different machines are calculated using the cGy per mAs provided in NCRP No. 102, Table B.3 (1989) for specific voltage, current, phase of the machine, and distance to the film.

Finally, the PORTS organ doses are found by multiplying the ICRP 34 organ dose conversion factors by the entrance air kerma values. The resulting PORTS x-ray organ doses for all machines are in Tables B.01 through B.04. The doses are shown in units of dose equivalent or rem, assuming a quality factor of 1.0 for x-rays. PORTS records will indicate the view and in most cases only one view was taken per medical examination.

3.4.1 Photofluorography (1954-1957)

Default values of entrance skin exposure have been developed for the three most commonly used occupational medical diagnostic x-ray procedures: P/A chest radiography; lateral chest radiography;

photofluorographic chest films when actual measurement data or knowledge of technique factors are absent and minimal collimation is assumed. The default values are considered to be maxima developed from review of patient doses as reported in the literature, machine characteristics, and knowledge of x-ray procedures used during the time periods indicated. Sufficient conservatism was included in the determination of the default values to ensure with near certainty that the actual exposures from the specified procedures would not exceed the default values, thus ensuring claimant favorability. In determining these factors, it was assumed that a minimum of filtration was used along with low kilovoltage techniques, slow film speeds with standard development, and no additional collimation or use of cones. The default entrance kerma values for the three procedures are given in Table 3-8. The PFG period of applicability is based upon the discovery of one PFG performed as appeared in one claimant's file in October of 1957. (ORAUT-OTIB-0006 2005)

Table 3-8. Default dose values by procedure.

Period	Entrance kerma, cGy P/A chest	Entrance kerma, cGy Lateral chest	Entrance kerma, cGy Photofluorographic chest
Pre-1970	0.20	0.50	3.0

The above default values can then be used as described above in lieu of actual measurement data or entrance kerma (ESE) derived from technique factors. These default ESE values were used in conjunction with uncollimated dose conversion factors as listed in the complex-wide x-ray TBD guidance document in Table 4.0-1 in ORAUT-OTIB-0006.

Organ doses for chest photofluorography are calculated in an analogous manner to organ doses calculated for conventional radiography using the ESE values. Table 4.0-1 provides dose conversion factors for the ICRP organs based on a distance of 152 cm and beam quality of 2.5 mm Al HVL.

3.4.2 Pre-1970 (1958-1969)

Prior to about 1970, x-ray measurement data, techniques, or beam port information may not be available to estimate the collimation of the x-ray beam. Several papers in the literature have considered the effects of cone size and centering on the organ dose, and concluded that filtration, kVp, and the smallest possible cone size were most important to reduce these doses (Feldman et al. 1958). Due to the reported variation in the literature and measurement data on the effects of collimation, it is claimant favorable to assume minimal or no additional external collimation was used when measurement data, technique, or other information to describe the collimation are not available for x-ray procedures performed prior to 1970.

Without collimation, organs normally outside of the primary beam are exposed to the primary beam. This necessitates the use of dose conversion factors from ICRP 34 other than those for a P/A or lat chest x-ray, since ICRP 34 dose conversion factors are based on properly collimated beams. For uncollimated beams used prior to 1970, the uncollimated dose conversion factors as listed in the complex-wide x-ray TBD guidance document in Table 4.0-1 were used. The entrance kerma values for pre-1970 x-ray machine that are used in the organ dose calculations are listed in Table 3-8. The calculation is analogous to the organ doses calculated for conventional radiography as illustrated in section 3.3.4.

3.4.3 Type I Machine (1970-1978)

Default values as presented in Table 3-9 were obtained from the site wide x-ray medical dose technical basis document. The default values were determined from a review of patient doses as reported in the literature, machine characteristics, and knowledge of x-ray procedures used during the

time period indicated. In determining these factors it was assumed that a minimum of filtration was used along with low kilovoltage techniques, slow film speeds with standard development, and no additional collimation or use of cones (ORAUT-OTIB 2005). An HVL of 2.5 mm was used in the organ dose calculations.

Table 3-9. Default dose values by procedure.

Period	Entrance kerma, cGy P/A chest	Entrance kerma, cGy Lateral chest
1970-1978	0.20	0.50

3.4.4 Type II Machine (1979-1991)

Based on the techniques in Table 3-3, the mAs for the types of equipment were calculated for each view:

Current (mA) × Exposure Time (sec) = Current for View (mAs) (3–1)
Example for Type II P/A view: 200 mA × 1/10 s = 20 mAs

The air kerma rate for 110 kVp was determined to be 0.25 cGy per 100 mAs (see Table B.3 of NCRP 102) and the air kerma was calculated after converting the rate to air kerma per mA.

Current for View (mAs) × Corrected Air Kerma Rate (cGy/mAs) = Air Kerma (cGy) (3–2)
Example for Type II P/A view: 20 mAs × 0.0025 cGy/mAs = 0.05 cGy

Multiply by 0.6 to account for 3.5 mm Al versus 2.5 mm Al Table B.3 NCRP 102 is based upon; (3–3)
{see Table 3-7} 0.6 × .05 cGy = .030 cGy

The air kerma was corrected for the thickness of the chest (26 cm) and for distance between the chest and the plane of the film (5 cm) to obtain the air kerma at skin entrance.

Air kerma at 183 cm x SID squared ÷ SSD squared = air kerma at skin entrance (3–4)
Example for Type II P/A view: 0.03 cGy × $(183\ cm)^2 \div (152\ cm)^2$ = 0.043 cGy

Air kerma at skin entrance was multiplied by the dose conversion factors in Table A.2 through A.8 of ICRP Publication 34 for P/A chest and HVL of 3.5 mm Al eq.

Air Kerma (cGy) × Dose conversion factor = Dose for View (cGy) (3–5)

Example for Type II P/A view, dose to thyroid:
0.043 cGy × 62 mGy/Gy × 1 Gy/100cGy × 1 rad/10 mGy = 2.67 E-3 rad

3.4.5 Type III Machine (1992-Present)

The survey measurements made by the FDA in 1992 which yielded 0.64 mR/mAs will be utilized to estimate the ESE. As indicated in Table 3-7 a linear adjustment for mA is needed. The technique factor for time used was 0.1 seconds and probably less because of the photo-timing system. The technique factor for kVp was 110 and for the current technique factor was 200 mA, the same parameters used for the FDA measurements. Therefore, no adjustments are needed for these technique factors. All other parameters were the same. The ESE calculation adjustment based on the 1992 FDA measurements is as follows:

0.64 mR/mAs × 0.1 sec × 200 mA = 12.80 mR

The FDA survey was used instead of the PORTS survey conducted in 1994 because the FDA measurement included the use of a phantom and is likely more reliable.

Based on the techniques in Table 3-3, the mAs for the types of equipment were calculated for each view in the same manner as presented in section 3.3.4 above. Table 3-10 lists the reference organ used to approximate the organ analogue doses.

Table 3-10. Analogues for IREP organs not included in ICRP 34.

Anatomical location	ICRP 34 reference organ	IREP organ analogues
Thorax	Lung	Thymus Esophagus Stomach Bone surface Liver/gall bladder/spleen Remainder organs
Abdomen	Ovaries	Urinary/bladder Colon/rectum
Head and neck	Thyroid	Eye/brain

3.5 UNCERTAINTY

Error, defined as deviation from the correct, true or conventionally accepted value of a quantity, and uncertainty, defined in terms of the potential range of a stated, measured, assumed or otherwise determined value of a quantity, provides an indication of the confidence of the dose estimates. Error implies knowledge of what the correct or actual value is, which is, of course, not known. Hence a more appropriate term is uncertainty, which is expressed in terms of a confidence level, e.g. 99% (i.e. that the correct or true value, although not actually known, has a 99% probability of falling within the range cited) and includes both precision or reproducibility of the measurement and accuracy, or how close the measurement or estimate of dose comes to the actual or correct value (ORAUT-TKBS-0003 2003, p5).

Although in theory a large number of factors can introduce uncertainties or affect the x-ray machine output intensity and dose to the patient, in practice only four factors can be reasonably considered to have an impact on dose uncertainty. These are 1) variation in applied kilovoltage, 2) variation in beam current, 3) variation in exposure time, and 4) distance from the patient to the source of the X rays (SSD). The influence of such other factors as use of screens, grids, reciprocity failure, film speed and development, while potentially variable, would not affect the beam output intensity (ORAUT-TKBS-0003 2003, p5).

For a given set of machine settings and parameters, x-ray output should theoretically be constant and unvarying. However, this is not true in practice; although output is essentially constant unless focal spot loading occurs such as might be the case when the power rating of the machine is exceeded. It is unlikely that power ratings were ever exceeded since so doing would be difficult to achieve in practice and would result in damage to the x-ray tube. However, even with the use of so-called constant voltage transformers to control line voltages, slight variations may occur in line voltage input or other internal voltages, which in turn could alter the kVp of the output beam. In general, for a given kVp setting, variation in kVp falls within ± 5% of the machine setting (Siebert et al. 1991). Since as noted above beam intensity is approximately proportional to the 1.7 power of the kilovoltage, this translates to an uncertainty of approximately ± 8.7%with respect to output beam intensity in the 80 to

110 kVp range used for diagnostic radiographs at the PORTS Site . For conservatism, this is rounded up to ± 9% (ORAUT-TKBS-0003 2003, p 5 and ORAUT-TKBS-0006-3 2003, p 14).

Similarly slight variations in tube current are normal; as a tube ages, or heats up from usage, tube current may change and typically will drop. Hence, all other factors remaining constant, beam intensity will be reduced, and in direct proportion to the change in tube current. Typically, the reduction in beam output from current variation is not more than a few per cent under normal operating conditions; large decreases in beam output will be readily detected and result in maintenance on the machine to restore the output or, as a temporary stopgap measure, increase in the current or kVp to provide the necessary intensity for proper radiography. There is no evidence to suggest that these stopgap measures were ever necessary or applied at the PORTS Site. For a given kVp setting, output of the beam is a function of the tube current, which in turn is measured by a milli-ammeter on the machine and measures average tube current. The measurement is subject to uncertainties, and in addition there may be minor changes in output as the tube heats up from normal usage. These variations are typically small, and hence uncertainty in beam output attributable to current variation has been estimated at ± 5% (ORAUT-TKBS-0003 2003, p 6).

Another parameter that has potential to affect the dose, perhaps significantly, from a diagnostic radiograph relates to the time of exposure. This can be readily understood by noting that a full wave rectified machine produces 120 pulses per second of x-rays. For an exposure time of 1/20 of a second, only six pulses would result. A small error in the timer that resulted in a change of only ± 1 pulse would correspondingly affect the output by ± 17%; for an exposure time of 1/30 of a second, the change in output corresponding to a deviation of ±1 pulse is ± 25%. Early mechanical timers were notoriously inaccurate, although timer accuracy improved significantly with the introduction of electronic timers. PORTS timer was held to a +/- 10 % criteria from about 1979. However, once again for conservatism, uncertainty in beam output attributable to timers will be assumed to have an upper limit of + 25% (ORAUT-TKBS-0003 2003, p 6).

The final factor that is likely to affect patient dose relates to distance from the source of the x-rays, which is a determinant of the entrance skin exposure. For a given individual, the SSD will be determined largely by the thickness of the patient, and how accurate the positioning is. For a typical patient, this variation in SSD is estimated at no more than a few centimeters, with an upper limit of perhaps 7.5 cm. Using Inverse Square, this indicates an uncertainty of ± 10% from this source (ORAUT-TKBS-0003 2003, p 6).

There are two approaches to determination of the combined uncertainty from the above four potential sources of uncertainty. The first, and most conservative in that it gives the greatest range, would be to assume that the uncertainties are additive, which would give an uncertainty range of up to 9 + 5 + 25 + 10 = 49. However, a more reasonable approach would be to assume that the uncertainties are in fact random, and to compute the statistical root mean square (RMS) value. The RMS value is simply the square root of the sum of the squares, and computes as ± 28.8%. Thus, for any individual entrance skin exposure (ESE) or derived organ dose, an uncertainty of ± 30 % l may be assumed; for further conservatism it may be appropriate to assume that errors are all positive, and only the + 30 % should be used (ORAUT-TKBS-0003 2003, p 6).

3.6 DOSE RECONSTRUCTOR INSTRUCTIONS

The information below provides instructions for dose reconstructors in determining organ doses from occupational medical (x-ray) procedures. For the purpose of evaluating probability of causation, x-ray doses are always considered acute, and are photons with energy E=30-250 keV.

3.6.1 Assignment of Organ Doses from X-ray Procedures: Approach for Dose Reconstructions

Maximizing Medical X-ray Dose

The organ doses assigned for each x-ray procedure are the highest doses to any organ in the relevant group as listed in Tables B1-B4 should be multiplied by a factor of 1.3 to account for uncertainty. The result will be the maximizing of annual x-ray doses that may be applied in dose reconstructions for likely non-compensable cases. At least one x-ray per year or partial year of employment should be assumed taken in order to be claimant favorable.

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A.0 PORTS MEDICAL X-RAY

PORTS conducted pre-employment and annual physical examinations as part of their occupational health program. These examinations typically included a P/A chest x-ray. For some workers, and occupations, chest x-rays could be more frequent.

A.1 ORGAN DOSES FROM MEDICAL X-RAYS

X-ray organ dose equivalents for occupational x-rays at PORTS are estimated for all years from 1954 to present. The schedule for these exams for all PORTS employees over this time period is shown in Table A-1 through A-2, along with the organ dose information. Tables A-3 and A-4 are for P/A views for listed and unlisted organs in ICRP 34. X-ray organ dose estimates were made for photofluorography (1954-1960), per-1970 (1961-1969), Type I equipment (used from 1970 to 1978), Type II equipment (used from 1979 to 1991) and Type III equipment (used from 1992 to present).

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Table A-1. Dose equivalents for organs identified in ICRP 34 (1982) for P/A views.

Period	Frequency	PORTS employee	Organ dose equivalents per 14" x 17" P/A chest (rem)							
			Air kerma at skin entrance[a]	Thyroid[d]	Ovaries[d]	Testes[d]	Lungs[d]	Breast[d]	Uterus[d] (embryo)	Bone marrow[d]
1954-1957 (PFG)[b]	Annual	All	3.000	0.52	0.025	0.005	1.350	0.147	0.025	0.276
1958-1969 (Pre-1970)[c]	Annual	All	0.200 minimal collimation	0.0348	0.025	0.005	0.0902	0.0098	0.025	0.0184
1970-1978 (Type I)	Annual	All	0.100 2.5 mm HVL	0.0032	0.0001	0.000001	0.0451	0.0049	0.00013	0.0092
1979-1991 (Type II)	Annual	All	0.043 3.5 mm HVL	0.00267	0.000138	0.00000043	0.0262	0.00391	0.000129	0.00628
1992-present (Type III)	Offered every 10 years	Employees up to 30 years old.	0.0128 3.5 mm HVL	0.000794	0.000041	0.000000128	0.00781	0.00116	0.0000384	0.00187
	Offered every 5 years	Employees up to 45 years old.								
	Offered every 3 years	Employees greater than 45 years old.								
	Annually	Asbestos /Beryllium workers.								

a. Air kerma at entrance skin in rem.
b. Photofluorographic chest entrance uncollimated kerma (2.5 mm Al HVL) ORAUT-OTIB-0006, Table 4.0-1.
c. Pre-1970 chest 99% confidence entrance uncollimated kerma (2.5 mm Al HVL) ORAUT-OTIB-0006, Table 4.0-1.
d. Organs identified in ICRP 34 (1982) for dose determination from air kerma skin entrance dose equivalent associated with chest radiography.

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Table A-2. Dose equivalent for IREP organs not included in ICRP 34 (1982) for P/A views.

Period	Frequency	PORTS employee	Organ dose equivalents per P/A chest (rem)										
			Air kerma	Thymus	Esophagus	Stomach	Bone surface	Liver/gall bladder/spleen	Urinary/ bladder	Colon/ rectum	Eye/brain	Skin[c]	Remainder
1954-1957 (PFG)[a]	Annual	All	3.000	1.35	1.35	1.35	1.35	1.35	0.025	0.025	0.096	4.05	1.35
1958-1969(Pre-1970)[b]	Annual	All	0.200 minimal collimation	0.0902	0.0902	0.0902	0.0902	0.0902	0.025	0.025	0.0064	0.270	0.0902
1970-1978(Type I)	Annual	All	0.100 2.5 mm HVL	0.0451	0.0451	0.0451	0.0451	0.0451	0.0001	0.0001	0.0032	0.135	0.0451
1979-1991 (Type II)	Annual	All	0.043 3.5 mm HVL	0.0262	0.0262	0.0262	0.0262	0.0262	0.000138	0.000138	0.00267	0.0602	0.0262
1992-present (Type III)	Offered every 10 years	Employees up to 30 years old.	0.0128 3.5 mm HVL	0.00781	0.00781	0.00781	0.00781	0.00781	0.0000451	0.0000451	0.000794	0.0179	0.00781
	Offered every 5 years	Employees up to 45 years old.											
	Offered every 3 years	Employees greater than 45 years old.											
	Annually	Asbestos/ beryllium workers.											

a. Photofluorographic chest entrance uncollimated kerma (2.5 mm Al HVL) ORAUT-OTIB-0006, Table 4.0-1
b. Pre-1970 chest 99% confidence entrance uncollimated kerma (2.5 mm Al HVL) ORAUT-OTIB-0006, Table 4.0-1
c. Entrance skin dose is entrance skin exposure calculated from air kerma, multiplied by a backscatter factor of 1.4 from NCRP 102, Table B-8.

Table A-3. Dose equivalents for organs identified in ICRP 34 (1982) beam quality for LAT views.

Period	Frequency	PORTS employee	Organ dose equivalents per LAT chest (rem)							
			Air kerma at skin entrance[a]	Thyroid[c]	Ovaries[c]	Testes[c]	Lungs[c]	Breast[c]	Uterus[c] (embryo)	Bone marrow[c]
1958-1969 (Pre-1970)[a]	Annual	All	0.500 uncollimated	0.0685	0.013	0.0025	0.1100	0.128	0.013	0.0185
1970-1978 (Type I)	Annual	All	0.250 2.5 mm HVL	0.0288	0.00015	0.000025	0.055	0.0638	0.00015	0.00925
1979-1991 (Type II)	Annual	All	0.108 3.5 mm HVL	0.0162	0.000172	0.0000108	0.0333	0.034	0.000151	0.00656
1992-present (Type III)	Offered every 10 years	Employees up to 30 years old.	0.032 3.5 mm HVL	0.00483	0.0000512	0.0000032	0.00992	0.0101	0.0000448	0.00195
	Offered every 5 years	Employees up to 45 years old.								
	Offered every 3 years	Employees greater than 45 years old.								
	Annually	Asbestos/ beryllium workers.								

a. Air kerma at entrance skin in rem.
b. Pre-1970 chest entrance uncollimated kerma (2.5 mm Al HVL) ORAUT-OTIB-0006, Table 4.0-1.
c. Organs identified in ICRP 34 (1982) for dose determination from air kerma skin entrance dose equivalent associated with chest radiography.

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Table A-4. Dose equivalent for IREP organs not included in ICRP 34 (1982) for LAT views.

Period	Frequency	PORTS employee	Organ dose equivalents per LAT chest (rem)										
			Air kerma	Thymus	Esophagus	Stomach	Bone surface	Liver/gall bladder/ spleen	Urinary/ bladder	Colon/ rectum	Eye/ brain	Skin [b]	Remainder
1958-1969 (Pre-1970)[a]	Annual	All	0.500 uncollim-ated	0.110	0.110	0.110	0.110	0.110	0.013	0.013	0.0685	0.675	0.110
1970-1978 (Type I)	Annual	All	0.250 2.5 mm HVL	0.055	0.055	0.055	0.055	0.055	0.00015	0.00015	0.0288	0.338	0.055
1979-1991 (Type II)	Annual	All	0.108 3.5 mm HVL	0.0333	0.0333	0.0333	0.0333	0.0333	0.000172	0.000172	0.0162	0.151	0.033
1992-present (Type III)	Offered every 10 years	Employees up to 30 years old.	0.032 3.5 mm HVL	0.00992	0.00992	0.00992	0.00992	0.00992	0.0000512	0.0000512	0.00483	0.0479	0.00992
	Offered every 5 years	Employees up to 45 years old.											
	Offered every 3 years	Employees greater than 45 years old.											
	Annually	Asbestos/ beryllium workers.											

a. Pre-1970 chest entrance uncollimated kerma (2.5 mm Al HVL) ORAUT-OTIB-0006, Table 4.0-1
b. Entrance skin dose is entrance skin exposure calculated from air kerma, multiplied by a backscatter factor of 1.4 from NCRP 102, Table A-8