ORAU Team **NIOSH Dose Reconstruction Project** Technical Basis Document for the K-25 Site - Occupational Medical Dose	Document Number: ORAUT-TKBS-0009-3 Effective Date: 11/07/2006 Revision No.: 00 PC-1 Controlled Copy No.: _____ Page 1 of 13
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RECORD OF ISSUE/REVISIONS

ISSUE AUTHORIZATION DATE	EFFECTIVE DATE	REV. NO.	DESCRIPTION
06/29/2004	06/29/2004	00	New technical basis document for the Oak Ridge Gaseous Diffusion (K-25) plant – Occupational Medical Dose. First approved issue. Initiated by Jay J. Maisler.
06/29/2004	11/07/2006	00 PC-1	Approved page change revision to update required language on pages 4 and 5 in Section 3.1. Updates acronyms and abbreviations on page 3. Adds a Purpose Section and a Scope Section on page 5. No sections were deleted. No further changes occurred as a result of formal internal review. No changes required to this document due to Worker Outreach comments This revision results in no change to the assigned dose and no PER is required. Training as required by Task Manager. Initiated by Paul A. Szalinski. Approval: Signature on File 10/24/2006 Paul A. Szalinski, Document Owner Signature on File 10/20/2006 John M. Byrne, Task 3 Manager Signature on File 10/24/2006 Edward F. Maher, Task 5 Manager Signature on File 10/23/2006 Kate Kimpan, Project Director Signature on File 11/07/2006 James W. Neton, Associate Director for Science

ACRONYMS AND ABBREVIATIONS

cm	centimeter
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
GE	General Electric
HVL	half-value layer
IREP	Interactive RadioEpidemiological Program
kVp	kilovolt peak
LAT	lateral
mA	milliampere
mAs	milliampere-second
mm	millimeter
NIOSH	National Institute for Occupational Safety and Health
PA	posterior-anterior
POC	probability of causation
RMS	root mean square
SID	source-to-image distance
SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
§	section or sections

3.1 INTRODUCTION

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 for particular sites or categories of sites. The documents 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 POC 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 covered facilities in its dose reconstructions for employees at DOE facilities, including radiation 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

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

- Radiation from diagnostic X-rays received in the treatment of work-related injuries

3.1.1 Purpose

This TBD documents historical practices at the Oak Ridge K-25 gaseous diffusion plant and provides information for the evaluation of medical exposure data for workers.

3.1.2 Scope

The K-25 occupational health and safety program required preemployment, annual physical, and health monitoring examinations. These examinations typically included diagnostic chest X-rays. The doses from these procedures depended on the characteristics of the X-ray machine and the procedure used.

3.2 EXAMINATION FREQUENCIES

During the early years at K-25, when little was known about health effects of working with uranium, X-ray examinations were frequent in an effort to monitor worker health. Table 3-1 lists the nominal frequency of examinations over the years during which work-related X-rays were required. Some workers might have received occupational X-rays on a schedule different from that listed in Table 3-1. The reconstruction of occupational dose should include all occupational X-rays according to the frequency listed in Table 3-1 unless the individual-specific frequency is known and is more frequent than that in Table 3-1. (Since chest X-rays were no longer required for non-radiation workers after 1959, this procedure is favorable to claimants.)

Table 3-1. Frequency of occupational chest X-rays at K-25.

Period	Frequency	Comment
1944–1945	Annual a	All employees
1946–1959	Annual b	All employees
1960–1979	Annual	All radiation workers.
1980–2002	Every 5th year	All radiation workers

a. Some workers monthly, with potential for exposure to uranium dust.
b. Some workers every few months, with potential for exposure to uranium dust.

3.3 EQUIPMENT AND TECHNIQUES

The earliest X-rays at K-25 used the photofluorographic technique. Photofluorography had widespread use throughout the United States for tuberculosis screening in the 1930s and was state-of-the-art medical technology when work began at the gaseous diffusion plant as part of the Manhattan Project. The photofluorography technique was phased out in favor of the current conventional X-ray exam.

Two X-ray machines were used at K-25 during the 1940s and 1950s: (1) a General Electric (GE) Model KX-10 Photoroentgen X-ray machine, used primarily for photofluorography of the chest, and (2) a Westinghouse 200-mA X-ray machine, used with an adjustable table and fluoroscopic attachment to examine extremities, spine, hips, skull, shoulder, and other nonthoracic locations. The Westinghouse machine, which produced the now-conventional 14-in. x 17-in. chest X-ray, was primarily a backup to the GE machine (Cardarelli 2000). The GE machine was used with a lyselia grid to produce miniature 4-in. x 5-in. stereoscopic posterior–anterior (PA) chest X-rays (Cardarelli 2000). The stereoscopic technique produces two images of the chest (on 4-in. x 10-in. film) at slightly different angles, resulting in a three-dimensional image of the chest when viewed through a stereoscope (Mason 1944; Hemphill and Diercks 1945).

Different techniques were used to produce PA chest X-rays with the Westinghouse and GE machines (Cardarelli, 2002). The Westinghouse X-ray beam passes through the chest and directly exposes the film to produce an image of the chest (Quinn 1945). The GE photofluorographic X-ray beam passes through the chest and produces an image on a fluorescent screen. The fluorescent image is photographed in two views for the stereoscopic image (Verstandig and Ainsworth 1944). The photofluorographic technique delivered a higher radiation dose to the subject because more exposure time was required to produce a photograph from the dim fluorescent image. Improvement in film and film processing enabled the phasing out of the photofluorographic technique in favor of film/intensifying screen imaging.

The K-25 site used only the conventional PA chest X-ray technique for routine examinations after the early 1950s, which substantially reduced radiation doses per examination. In 1962, a Westinghouse 300-mA machine replaced the 200-mA machine. Additional X-ray exposure was introduced in the early 1970s when the health monitoring program added a lateral (LAT) chest view to the routine chest X-ray examination procedure (Cardarelli 2000). In 1987, a Westinghouse 500-mA X-ray unit replaced the 300-mA machine. Routine PA and LAT chest views were performed through 2000.

This document assumes that K-25 medical practices followed the standards of radiology practice during the 1930s and 1940s. Nevertheless, workers might have received their largest occupational doses from the required medical X-ray examinations. The amount of dose received depends on the type of equipment, the technique factors, and the number of examinations typical in the early years (Cardarelli 2002). K-25 medical records include notations in individual worker files regarding the date and the purpose of the of X-ray examinations.

The occupational medical program at K-25 from 1945 to 2000 used three diagnostic radiographic procedures in connection with preemployment, health monitoring, or postemployment medical examinations:

1. 4-in. × 5-in. PA photofluorographic film
2. Posterior-anterior 14-in. × 17-in. chest film
3. Lateral chest film

Doses from these three techniques were evaluated for assigning occupational dose. Other radiographic examinations of K-25 employees that might have occurred were nonoccupational in the sense that they were necessitated by illness or injury and were not part of the employee physical examination process.

Table 3-2 lists the X-ray equipment used at K-25 and the entrance skin exposure (ESE) produced by the machines (Cardarelli 2002). The ESEs in Table 3-2 are all from actual measurements made and documented in the literature.

3.4 ORGAN DOSE CALCULATIONS

Estimated organ doses for PA and LAT chest X-rays were based on the dose conversion factors in ICRP (1982). Organ doses from LAT chest radiography were greater than those from the corresponding PA doses based on the greater mAs exposure per radiograph and the smaller SSD.

ICRP (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 and selected beam qualities [i.e., various half-value layers (HVLs)]. These tables list the basic dose conversion factors for converting air kerma to organ dose. Air kerma was obtained from Table 3-2 for

Table 3-2. X-ray equipment used at K-25 (Cardarelli 2002).

Period	X-ray machine	kVp (kV)	Assumed HVL (mm Al eq)	Image size (inches)	Entrance skin exposure (cGy)	
					PA	LAT
1944-1956	GE KX-10	80	2.5	4 x 5	2.488[a]	
1944-1962	Westinghouse 200-mA	65	2.5	14 x 17	0.055[b]	
1962-1969	Westinghouse 300-mA	90	2.5	14 x 17	0.015[c]	
1970-1986	Westinghouse 300-mA	150	4	14 x 17	0.010[d]	0.030[d]
1987-2000	Westinghouse 500-mA	150	4	14 x 17	0.022[d]	0.035[d]

a. Quinn 1945; Cardarelli 2000.
b. Lincoln and Gupton 1957.
c. Gupton et al. 1956 on comparable unit.
d. Cardarelli (2000); conservatively assumed 150 kVp and 4 mm Al HVL.

machine, view, and period by assuming R = cGy (kerma). This assumption is conservative. The estimation is made by equation 3-1, where *ESE* is the entrance skin exposure in R = cGy = rem, *DCF* is the dose conversion factor in mGy/G = millirem/rem, and *D* is dose in millirem.

$$ESE \times DCF = D \quad (3\text{-}1)$$

Table 3-3 lists the results of Equation 3-1 for the organs listed in ICRP (1982). The results of Table 3-3 assume poor collimation prior to 1970, which means that some organs are included in the primary beam that would not normally be had the beam been properly collimated.

The Interactive RadioEpidemiological Program (IREP) code specifies organs for which there are no ICRP (1982) dose conversion factors. Organs not listed in Table 3-3 can be assigned doses by analogy of anatomical location – thorax, abdomen, and head/neck. The ICRP (1982) reference organs in these locations are lung, ovaries, and thyroid, respectively, as listed in Table 3-4. The dose for the analogous organ in Table 3-4 is assumed to be equal to that for the reference organ listed in Table 3-3 for the type of X-ray examination. Such a dose assignment will be conservative because the analog organ is more distant or more shielded than the reference organ.

3.5 UNCERTAINTY ANALYSIS FOR K-25 RADIOGRAPHY DOSES

Error (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) provide an indication of the confidence of the dose estimates. Error implies knowledge of the correct or actual value, which is, of course, not known. Therefore, the more appropriate factor is uncertainty, which is expressed in terms of a confidence level (e.g., 99% -- 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.

A large number of factors affect X-ray machine output intensity and, as a consequence, introduce uncertainty in the dose to the worker. Five factors produce the dominant dose uncertainty:

1. Variation in applied kilovoltage
2. Variation in beam current
3. Variation in exposure time
4. Distance from the worker to the source of the X-rays (SSD)

Table 3-3. Organ dose[a] per X-ray procedure for the various X-ray examinations from 1944 to 2000.

Organ	View	1944-1956 GE Model KX-10 Photofluorographic 4" x 5" 2.5 mm Al Dose (rem)	1944-1961 Westinghouse 200-mA X-ray 14" x 17" Dose (rem)	1962-1969 Westinghouse 300-mA X-ray 14" x 17" Dose (rem)	1970-1986 Westinghouse 300-mA X-ray 14" x 17" Dose (rem)	1987-2000 Westinghouse 500-mA X-ray 14" x 17" Dose (rem)
Thyroid	PA	4.33E-01[b]	9.57E-03[b]	2.61E-03[b]	7.80E-04	1.72E-03
	LAT				4.92E-03	5.74E-03
Eye/Brain	PA	7.96E-02[c]	1.76E-03[c]	4.80E-04[c]	7.80E-04	1.72E-03
	LAT				4.92E-03	5.74E-03
Ovaries	PA	2.07E-02	6.88E-03	2.52E-03	5.20E-05	1.14E-04
	LAT				7.50E-05	8.75E-05
Testes	PA	4.15E-03	1.38E-03	1.37E-04	1.00E-07	2.20E-07
	LAT				3.00E-06	3.50E-06
Lungs (male)	PA	1.04E+00	2.30E-02	6.29E-03	6.28E-03	1.38E-02
	LAT				9.39E-03	1.10E-02
Lungs (female)	PA	1.12E+00	2.48E-02	6.77E-03	6.74E-03	1.48E-02
	LAT				1.05E-02	1.23E-02
Breast	PA	1.22E-01	2.70E-03	7.35E-04	1.16E-03	2.55E-03
	LAT				1.03E-02	1.20E-02
Uterus	PA	3.23E-03	8.20E-03	2.24E-03	5.20E-05	1.14E-04
	LAT				6.30E-05	7.35E-05
Bone marrow (male)	PA	2.29E-01	5.06E-03	1.38E-03	1.78E-03	3.92E-03
	LAT				2.28E-03	2.66E-03
Bone marrow (female)	PA	2.14E-01	4.73E-03	1.29E-03	1.72E-03	3.78E-03
	LAT				1.77E-03	2.07E-03
Skin	PA	3.36E+00[d]	7.42E-02[d]	2.03E-02[d]	1.40E-02[e]	3.08E-02[e]
	LAT				4.20E-02[e]	4.90E-02[e]

a. Dose conversion Factors from Tables A.2 through A.9, ICRP Publication 34 (1982).
b. Dose conversion factor for AP C-spine multiplied by depth dose correction factor of 0.20.
c. Dose conversion factor for PA chest.
d. Entrance kerma multiplied by a backscatter factor of 1.35.
e. Entrance kerma multiplied by a backscatter factor of 1.40.

Table 3-4. Reference organs 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 (unless otherwise specified)	Eye, brain

The influence of such other factors as the use of screens, grids, reciprocity failure, film speed, and development, while potentially variable, does not appreciably affect the beam output intensity.

X-ray output should be constant and unvarying for a given set of machine settings and parameters. This is not true in practice, although output is essentially constant unless focal spot loading occurs, which could be the case if the power rating of the machine is exceeded. It is unlikely that power ratings were ever exceeded, because such an event would be difficult to achieve and could result in damage to the X-ray tube. Nevertheless, even with the use of so-called constant voltage transformers to control line voltages, slight variations might 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 setting, variation in kVp falls within + 5% of the machine setting (Seibert et al. 1991). Beam intensity is approximately proportional to the 1.7 power of the kilovoltage (Trout, Kelley, and Cathey 1952; Taylor 1957); this translates to an uncertainty of approximately ± 8.6% with respect to output beam intensity in the 80 to 100 kVp used for diagnostic radiographs at K-25. For conservatism, this is rounded up to ±9%.

Similar slight variations in tube current are normal; as a tube ages, or heats up from use, current can change and typically will drop. With all other factors constant, beam intensity will be reduced in direct proportion to the change in tube current. Typically, the reduction in beam output from current variation is not more than a few percent under normal operating conditions; large decreases are readily detectable and result in maintenance on the machine to restore the output or, as a temporary measure, an increase in the current or kVp to provide the necessary intensity for proper radiography. For a given kVp setting, the output of the beam is a function of the tube current, which in turn is measured by a milliammeter, which measures average tube current. The measurement is subject to uncertainties; there might be minor changes in output as the tube heats from normal use. Because these variations are typically small, the estimated uncertainty in beam output attributable to current variation is ± 5%.

Another parameter with the potential to affect the dose from a diagnostic radiograph, perhaps significantly, relates to the time of exposure. A full wave rectified machine produces 120 pulses of X-rays per second. In an exposure time of 1/20 of a second, 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. Accuracy improved significantly with the introduction of electronic timers. The assumed uncertainty in beam output attributable to timers has an upper limit of ± 25%.

The final factor likely to affect worker 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 body thickness of the worker and the accuracy of the positioning. For a typical worker, the estimated variation in SSD is no more than a few centimeters, with an upper limit of perhaps 7.5 cm. Using the inverse square, this indicates an uncertainty of ± 10% from this source.

The machine settings and parameters introduce random uncertainties and the total uncertainty is the root mean square (RMS) value. The RMS value is simply the square root of the sum of the squares, and computes as ± 28.9%. Rounding this up to ± 30% provides an adequate and suitably conservative estimation of uncertainty. Thus, for an individual ESE or derived organ dose, an uncertainty of ± 30% at a confidence interval of one standard deviation can be assumed. For further conservatism it might be appropriate to assume that errors are all positive, and only + 30% should be used.

3.6 DOSE RECONSTRUCTION

Worker X-ray examinations were recorded in individual medical histories. As described in Section 3.1, dose should be assigned based on recorded history rather than the frequencies listed in Table 3-1 when to recorded history is known and is more frequent than the data listed in Table 3-1. Otherwise, dose reconstruction should proceed on the basis of the nominal frequency listed in Table 3-1. The type of X-ray machine was probably recorded, so organ dose can be extracted directly from Table 3-3. For 1945 to 1956, when both the GE KX-10 and the Westinghouse 200-mA were used, Cardarelli (2002) estimates that the GE KX-10 was used for 86% of the examinations. Workers with lost records should be assigned the most appropriate frequency based on type of employment. The

assigned dose using Tables 3-3 and 3-4 and the number of examinations is a point estimate. Uncertainty should be applied as a normal distribution with an uncertainty of 30%.

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GLOSSARY

backscatter
A reflection x-rays from a nonreflective surface. The x-rays are scattered in all directions, including back in the direction from which it came.

dose
The amount of radiation energy deposited in a unit mass of tissue.

error
Deviation from the correct, true, or conventionally accepted value of a quantity.

gaseous diffusion plant
A facility where the percentage of uranium-235 is increased relative to uranium-238 by a filtering process using uranium hexafluoride gas.

kerma
Acronym for kinetic energy released per unit mass. Kerma is the sum of the initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation (neutrons and photons) in a sample of matter, divided by the mass of the sample. Kerma is expressed in gray (or its submultiples), and, unless otherwise specified, refers to the energy liberated per unit mass in a small sample of tissue. Free-in-air kerma refers to the amount of radiation at a location before adjustment for any external shielding from structures or terrain.

lyselia grid
A grid made of thin lead strips placed between the patient and the image to reduce the scattered radiation from the patient.

Manhattan Project
The code name for the U.S. effort to develop the atomic bomb.

occupational dose
Radiation dose received as the result of employment.

photofluorography
A radiographic procedure where the fluorescent image on a simple screen (without image intensifier) was recorded on film with a camera

photofluoroscopic
Viewing photographs taken of a fluoroscope (fluorescent screen imager for x-rays).

stereoscopic
Three dimensional viewing of photographic images, two views of the same image taken at slightly different angles

uncertainty
An estimate of the variety of a measurement, the amount a measurement may vary about its true value given the technique and circumstances of the measurement.

X-ray

Radiation emitted when matter is bombarded with fast electrons. Also, a picture produced by exposing photographic film to X-rays that traverse the body.