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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
09/15/2005	00	New Technical Basis Document for Pinellas – Site External Dose. First approved issue. Training required: As determined by the Task Manager. Initiated by Mark D. Notich.
08/03/2006	00 PC-1	Approved page change revision to incorporate changes according to the public outreach meetings in 09/2004 and 11/2005 and claimant communications. Updated required language on pages 6 and 7 in Section 6.1. Added Purpose and Scope Sections on page 7. Changes occurred on page 10, in Section 6.1.4, page 27 in Section 6.4.2, and on pages 29 - 32 in the Reference Section. As a result of internal formal review, changes were made to Tables 6-4, 6-5, 6-11, and 6-12 on pages 16, 17, 25, and 27, respectively in Sections 6.2.3 and 6.4.1.1 and 6.4.2. Wording was added or changed on pages 10, 15, 19, 23, 24, and 27, in Sections 6.1.1, 6.2.3, 6.2.4, 6.3, and 6.4.2.1. No sections were deleted. 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. Approval: Signature on File 07/25/2006 Paul J. Demopoulos, TBD Team Leader Signature on File 07/25/2006 John M. Byrne, Task 3 Manager Signature on File 07/24/2006 Edward F. Maher, Task 5 Manager Signature on File 07/27/2006 Kate Kimpan, Projector Director Signature on File 08/03/2006 James W. Neton, Associate Director for Science
11/08/2006	00 PC-2	Approved page change revision to incorporate changes according to Task 5 comment and Task 7 amendment to page 27 and 28 in Section 6.4.1.1. Corrects table numbering on page 28 and 29. Adds two references to page 34. Corrects GEND references on pages 20, 24, and 32. No sections were deleted. Incorporates internal formal review comments. Incorporates NIOSH formal review comments. Minor editorial changes were made on pages 24 and 29. Deletes Task 7 amendment to page 27 and 28 in Section 6.4.1.1. Corrects Table 6-5 rows 2 and 3 on page 18. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Paul J. Demopoulos. Approval: Signature on File 10/19/2006 Paul J. Demopoulos, 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, Projector Director Brant A. Ulsh Signature on File for 11/08/2006 James W. Neton, Associate Director for Science
04/28/2011	01	This technical basis document was predominantly revised to address SC&A's issues with the document, as identified in SCA-TR-TASK1-0015. Adjustments to certain photon dosimeter results now need to be made per Section 6.3.1.1. Photon LOD values specific to the Mound dosimeters are now provided in Table 6-10. Significant changes were also made on how neutron doses are assessed, and the new approaches are described in Section 6.3.2. The applicability dates for the various types of neutron dosimeters used at the site were changed, and are now in Table 6-11. In addition, a number of editorial changes were made to this document. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Brian P. Gleckler.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
ALARA	as low as reasonably achievable
Bq	becquerel
CFR	*Code of Federal Regulations*
Ci	curie
cm	centimeter
CPE	Ceramic Product Engineering
D	deuterium (^{2}H)
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOELAP	U.S. Department of Energy Laboratory Accreditation Program
DU	depleted uranium
EEOICPA	*Energy Employees Occupational Illness Compensation Program Act* of 2000
ft	foot
g	gram
GE	General Electric Company
GEND	GE Neutron Devices
GENDD	GE Neutron Devices Department
GEPP	GE Pinellas Plant
GEXF	GE X-ray Division in Florida
GEXM	GE X-ray Division in Milwaukee, Wisconsin
hr	hour
HSR	Health and Safety Record (system)
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
Landauer	R. S. Landauer Jr. & Co.
LOD	limit of detection
MeV	megaelectron-volt, 1 million electron-volts
mR	milliroentgen
mrem	millirem
n	neutron
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIO Office of Compensation Analysis and Support (OCAS) Claims Tracking System
NDD	Neutron Devices Department
NTA	nuclear emulsion type A film (a film used for certain neutron dosimeters)
ORAUT	Oak Ridge Associated Universities Team

PAO	Pinellas Area Office
POC	probability of causation
QA	quality assurance
RBE	relative biological effectiveness
RTG	radioisotopically-powered thermoelectric generator
SNL	Sandia National Laboratories
SRDB	ORAUT's Site Research Database
SRDB Ref ID	Site Research Database Reference Identification (number)
T	tritium (^3H)
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
yr	year
μCi	microcurie
α	alpha particle
§	section or sections

6.0 OCCUPATIONAL EXTERNAL DOSE

6.1 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 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, 42 C.F.R. Pt. 82) define “performance of duty” for DOE employees with a covered cancer or restrict the “duty” to nuclear weapons work (NIOSH 2010).

The statute also 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 excludes Naval Nuclear Propulsion Facilities from being covered under the Act, 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 occupational radiation exposures are considered valid for inclusion in a 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 (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

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

6.1.1 Overview

This TBD is Part 6 of the Pinellas Plant's Site Profile. A site profile provides a summary of information about a site that is relevant to the dose reconstruction process.

The Pinellas Plant has been known by several names throughout its history. Those names include: 908 Plant, Pinellas Peninsula Plant, GE X-ray Division-Florida (GEXF), GE Neutron Devices Department (GENDD), GE Neutron Devices (GEND), GE Pinellas Plant (GEPP), and the Pinellas Plant.

The General Electric Company built and operated the Pinellas Plant for DOE from its initial startup in January 1957 until June 1992. In June 1992, Martin Marietta Specialty Components, Inc. (MMSC) took over as the managing and operating contractor for the Pinellas Plant. In 1994, Lockheed merged with Martin Marietta and the managing and operating contractor for the Pinellas Plant was renamed Lockheed Martin Specialty Components (LMSC). The Pinellas Plant completed its war reserve fabrication of neutron generators at the end of September 1994, and began the transition from a defense mission to an environmental management mission. That transition included a number of decontamination and decommissioning activities that allowed the Plant to be turned over for commercial uses. LMSC continued as the managing and operating contractor until decontamination and decommissioning activities ended in 1997 (ORAUT 2011b).

The Plant was built to manufacture neutron generators, a principal component in nuclear weapons. The neutron generators consisted of a miniaturized linear ion accelerator assembled with pulsed electric power supplies. The ion accelerator, or neutron tube, required ultraclean, high-vacuum technology; hermetic seals between glass, ceramic, glass-ceramic, and metal materials; and high-voltage generation and measurement technology. The Plant manufactured only neutron generators for its first 10 years of operation. It later manufactured other products including neutron detectors, radioisotopically-powered thermoelectric generators (RTGs), high-vacuum switch tubes, specialty capacitors, and specialty batteries (Weaver 1990). As part of its program to promote commercial uses of the site, DOE sold most of the Plant to the Pinellas County Industry Council in March 1995 and leased back a portion through September 1997 to complete safe shutdown and transition activities (MMSC 1996).

6.1.2 Purpose

This TBD represents a specific support mechanism for documentation of external dosimetry historical practices at the Pinellas Plant. It can be used to evaluate external dosimetry data for monitored workers and can serve as a supplement to individual monitoring data. For unmonitored workers, information in this document will provide for estimations of external doses. This document provides a site profile of Pinellas that contains technical basis information to be used to evaluate the total occupational external radiation dose for EEOICPA claimants.

6.1.3 Scope

This document provides supporting technical data to evaluate the total Pinellas occupational radiation dose that can reasonably be associated with the worker's radiation exposure. This dose results from exposure to external radiation sources in Pinellas facilities that would be added to Plant occupationally required diagnostic X-ray examinations, and to onsite environmental releases, if applicable, to determine the total external dose. Also included are techniques to estimate the dose that might have occurred while an employee was not monitored or inadequately monitored; dose that might have been missed due to analytical detection limits; or dose for an employee whose monitoring records are incomplete or missing (i.e., missed dose). Over the years, new and more reliable scientific methods and protection measures have been deployed. The methods needed to account for these changes are also identified in this document.

This TBD describes the external dosimetry program at the Pinellas Plant. It discusses dose reconstruction, practices and policies at the Pinellas Plant, and dosimeter types and technologies for measuring dose from the different types of radiation present in the work environment. It also discusses the specific details of the evaluation of doses measured from exposure to electron (beta particles), photon (X-rays and gamma rays), and neutron radiation; sources of bias, workplace radiation field characteristics, responses of different dosimeters in the workplace radiation fields, and adjustments to the recorded dose measured by these dosimeters during specific years.

6.1.4 Sources of Radiation

The manufacture of Pinellas Plant products required the use of radioisotopes. The predominant radionuclides used at the Plant included tritium, depleted uranium (DU), ^{85}Kr, ^{238}Pu, and ^{239}Pu. In addition, the Plant used various analytical devices and calibration sources as part of the production process or for radiation detection device maintenance and calibration.

The predominant source of electron radiation at the Pinellas Plant was tritium, but this radionuclide emits only a low-energy beta particle with an average energy of 5.7 keV. Because electrons below 15 keV do not have sufficient energy to penetrate the epidermal layer of the skin (NIOSH 2007), tritium is not considered to be an external radiation hazard.

Starting in 1968, the Pinellas Plant stored tritium gas in beds of DU metal (MMSC 1994a, Phillips 1975). DU metal in sealed stainless-steel containers stored tritium at normal pressure and temperature (GE 1979; Ward 1973; Weaver 1990). Heating can decompose the tritium bonds in uranium tritide to release ultrapure tritium while the remaining DU metal is ready for fast and reversible uptake of tritium at lower temperatures. The DU metal was fully contained in the tritium storage vessel. The storage vessels should not have been a source of external electron radiation exposure.

Krypton-85, a beta and gamma emitter, was used in two leak detection units as part of the Pinellas Quality Control Program. The leak detection units were housed in separate rooms and surrounded by ventilation shrouds. Each shroud was connected to ductwork that exhausted to the east main exhaust stack. Because it is a noble gas, ^{85}Kr is a whole-body emitter with the possibility of a skin dose from electron radiation.

Small sealed sources of plutonium [consisting of 8.75 g and/or 10 g of source material, (GE 1982)] produced at another site were shipped to the Pinellas Plant for use in the RTGs. The radionuclide composition of each sealed plutonium source was approximately 80% ^{238}Pu, 16% ^{239}Pu, 3% ^{240}Pu, and 1% of other radionuclides by mass (GE 1982). The plutonium sources were enclosed in a triple metal encapsulation. These units were never opened. The capsules were inserted as heat sources for the RTGs (DOE 1983, pp. 2-11). The first recorded receipt of plutonium was on January 18, 1957, when the Plant received a 7-g (4.44×10^{12}-Bq or 120-Ci) ^{238}Pu source to calibrate Health Physics monitoring equipment. Seven plutonium heat sources arrived at Pinellas from Sandia National Laboratories on November 4, 1975 (GE undated a,b). About 50 RTG generators were produced every month (Burkhart 1987a, p. 4). The last onsite plutonium, with the exception of calibration check sources, was removed from the Plant in February 1991 (GE undated a,b).

Sources of ionizing radiation at the Pinellas Plant included other low-activity radioactive sources, such as those used to check or calibrate radiation detectors (i.e., calibration sources) and analytical devices employing radioactive byproduct material or X-rays produced by a radiation generating device. The calibration sources were maintained in the Health Physics Laboratory in Area 113 of

Building 100. While the exact inventory of radioactive sources varied over time, most were sealed microcurie check sources of radioactive isotopes such as ^{137}Cs, ^{238}Pu, ^{239}Pu, ^{60}Co, ^{14}C, and ^{90}Sr. These low-activity radioactive sources could have included alpha, electron, photon, and neutron emitters. For example, small quantities of ^{14}C-labeled solvents were used in a laboratory testing operation. The largest ^{14}C source was a 2.59×10^{7}-Bq (700-μCi) source used for liquid scintillation counting calibration. Radiation doses from ^{14}C resulted from internal deposition (DOE 1983). The analytical devices could have used radioactive byproduct material, such as ^{85}Kr, ^{109}Cd, or ^{241}Am, that requires U.S. Nuclear Regulatory Commission certification.

External sources of radiation at the Pinellas Plant included radiation generating devices. However, unlike radionuclide sources, radiation generating devices emit radiation only when they are turned on and activated. The most common type of radiation generating device at the Pinellas Plant was the primary product that it produced, which was the neutron generator. The neutron generators produced at the Plant were miniature accelerators that provided sources of fast neutrons for nuclear weapons. These miniature accelerators accelerated a beam of deuterium atoms into either a deuterium (D) or tritium (T) target (NCRP 1983). The resulting fast neutrons were produced by two different types of fusion reactions depending on the neutron generator design. Most neutron generators constructed at the Pinellas Plant produced 14-MeV neutrons via a $T(D,n)^{4}He$ reaction (NCRP 1983; Weaver 1994a; Barclay 1995). However, a few neutron generators were constructed to produce 2.5-MeV neutrons via a $D(D,n)^{3}He$ reaction (NCRP 1983; Weaver 1994a; Barclay 1995). These neutron generators also emitted X-rays from secondary reactions (NCRP 1983).

A full scale 200-keV Cockcroft-Walton ion accelerator was initially located in Room 161 of Building 100 for about 2 years before being moved to Building 800 (Weaver 1994a; Barclay 1995). The accelerator was used to accelerate deuterium ions into various tritium targets to determine the neutron output of those targets (MMSC 1995a, p. 5-5). The accelerator was also used to irradiate battery compound samples (such as lithium and silicon) with high-flux neutrons (MMSC 1995b).

6.1.5 <u>Occupational Dosimetry Program Overview</u>

The Pinellas Plant started an external dosimetry program in 1957 to monitor individual employees working in neutron generator production areas. Some Pinellas records on facility monitoring, safety evaluations, investigations, etc., exist; however, most of these records concern operations after 1970. Records of radiation dose to individual workers from personnel dosimeters are generally available for 1957 to 1994 for the workers' time of employment. The dose measured by dosimeters was recorded at the time of measurement, reviewed by Pinellas health physicists, and routinely made available to workers. *External Dose Reconstruction Implementation Guidelines* (NIOSH 2007) indicates that these records represent the highest quality record for a retrospective dose assessment. The information in this section pertains to the analysis of the available records.

Table 6-1 lists the total number of Pinellas employees and the number of employees monitored for radiation exposure for years that this type of data was available. From 1960 to 1973, U.S. Atomic Energy Commission (AEC) annual exposure summary reports indicate that Pinellas had 27.5% of its labor force wearing dosimetry (377 of an average yearly labor force of 1,372). During the 1980s, while the data are not completely available, from 370 to approximately 400 of 1,650 to 1,975 workers (approximately 20%) were monitored for radiation dose. For the majority of Pinellas operations, external dosimetry was exchanged and analyzed monthly. Beginning in January 1990, external dosimetry was exchanged and analyzed quarterly (Burkhart 1988; Weaver 1990).

Table 6-1. Personnel radiation dosimetry from AEC annual reports.[a]

Year	Number of PAO-AEC (or DOE) and GEND employees	Number of monitored employees	Number of employees in a given dose range	
			< 1 rem	1–2 rem
1960	1,304	225	225	0
1961	1,395	251	251	0
1962	1,370	254	254	0
1963	1,597	545	545	0
1964	1,408	347	347	0
1965	1,319	301	301	0
1966	1,445	325	325	0
1967	1,405	585	584	1
1968	1,397	281	281	0
1969	1,323	588	588	0
1970	1,311	442	441	1
1971	1,283	410	410	0
1972	1,402	346	346	0
1973	1,252	383	383	0
1974	NA[b]	NA	NA	NA
1975	NA	NA	NA	NA
1976	NA	317	317	0
1977	NA	300	300	0
1978	NA	297	297	0
1979	NA	334	334	0
1980	NA	376	376	0
1981	NA	389	389	0
1982	NA	408	408	0

a. Source: Data from Form AEC-190.
b. NA – not available.

No documentation was found to show that all employees were monitored at some time during Pinellas operations, and it is evident that not all groups of workers were required to wear dosimeters (ORAUT 2005a). However, the Pinellas Plant was not required to monitor most employees because most of the work being performed did not expose personnel to external dose and because most personnel did not have routine access to radiation areas.

The external dosimetry assignment procedure has changed over the history of the Pinellas Plant. The earliest practices likely were based on regulatory requirements that required control of access, occupancy, and working conditions for radiation protection purposes (NBS 1958) and subsequently quarterly dose limits of 1.25 rem/quarter (AEC 1960). The AEC annual report information summarized in Table 6-1 illustrates that nearly all the personnel who were monitored for external dose were monitored when their annual exposures were less than 1.25 rem/yr. General operating procedures for the Pinellas Plant from as early as 1967 indicate that dosimeters were assigned to all personnel with a potential to receive a measurable external dose. This is confirmed by the annual whole-body doses that indicate that on average more than 79% of the monitored workers at the Plant received an annual whole-body dose of less than or equal to 0.02 rem for any given year (see Table B-1 in Attachment B). Given this information, any personnel with the potential to receive a measurable external dose at the Pinellas Plant were likely monitored for external dose.

A GE general operating procedure titled “Film Badge Requirements,” dated May 10, 1967, states that it was management’s responsibility to “[a]scertain that film badges are worn by all personnel whose work assignments entail the potential for accumulating measurable radiation exposures; compliance with this procedure is a condition of employment in a Radiation Area” (GE 1957–1990). All versions of a GE general operating procedure titled “Assignment of Personnel to Work in Radioactive Material, Contamination, or Radiation Areas,” dated between January 17, 1968, and June 29, 1984, state that it was the Work Area Manager's responsibility to "[e]nsure that all employees having work assignments in Radiation Areas are provided with film badges" (GE 1957–1990). In addition, a GE memorandum dated November 1, 1984, states that "[a]ll individuals with a potential of receiving measurable radiation dosage are included in our personnel monitoring program" (Greene 1984a).

6.2 DOSE RECONSTRUCTION PARAMETERS

6.2.1 Historical Administrative Practices

Between 1957 and 1974, GEND-Health Physics conducted radiation dosimetry management and analysis through in-plant processing of X-ray and neutron-sensitive photographic films (Burkhart 1987b). During 1965, GEND compared performance of GEND in-house processing results with commercial services from Landauer and Nuclear-Chicago for selected gamma and neutron doses, respectively, which showed essentially equivalent performance (Szedziewski 1965). In 1974, GEND contracted with R. S. Landauer Jr. & Co. (Landauer) to be the principal supplier and processor of the dosimetry that GEND used. This arrangement continued until Pinellas Plant operations ended.

The available information indicates that, from the start of nuclear operations in 1957, the Pinellas Plant used film badge dosimetry available from or similar to the type sold by Nuclear-Chicago for the designated radiation control areas (GE 1957–1990). During the period that the Pinellas Plant read its own dosimeters, the available film work sheets indicate that only the open window (OW) film was read from the film dosimeters and the OW result was reported as photon dose (GE 1957–1990, pages 67 and 99). This practice likely resulted in the photon doses reported for the period of 1957– June 1974 being overestimates of the workers actual photon doses, because a significant portion of the Pinellas Plant's photon doses were attributable to < 250 keV photons and because the OW portions of the early film dosimeters typically over-responded to the lower energy photons (ORAUT 2005c, 2006b). Because specific information on dosimeter design and dosimeter calibration could not be confirmed for the period of 1957– June 1974, no adjustments to the reported photon doses are recommended, to account for the over-response that the dosimeters likely had to the photon radiation at the Plant. The practice of only reading the OW film and reporting the result as photon dose would also explain why non-penetrating doses such as electron doses were not reported during this era. In addition, any potential electron doses received by the workers would have been accounted for and reported as photon doses by this practice.

An unsigned note in a collection of highly varied examples of dosimetry records, which include a number of records from the GEXM site, indicates that personnel monitoring for neutrons might not have began at the Pinellas Plant until 1960, and neutron doses for the period from 1957 through May 1960 might have been estimated from area monitors (GE 1957–1990). Even if the note is accurate about neutron monitoring at the Plant, it should not have an adverse effect on the neutron dose calculations for that period. Because the same whole-body dosimeters were used for personnel and area monitoring, the neutron dose calculations would be the same regardless of whether the worker's neutron doses were based on a personnel dosimeter or a dosimeter used to monitor an area.

Beginning in July 1974, the Plant began using dosimetry provided exclusively by Landauer. The original Landauer dosimetry was based on film badge technology (Ward 1974). Landauer processed the dosimetry and provided exposure reports to GEND for review after badge processing. Figure 6-1 is a replication of a portion of a Landauer dosimetry report (Landauer 1986-1988). Information in the Landauer reports included personnel data (identification number, name, and social security number), dosimeter type, deep and shallow exposure for the reporting period (i.e., monthly), and cumulative totals for deep and shallow exposures for the calendar quarter, year to date, and permanent exposure (lifetime exposure at Pinellas). The exposure information was entered in each person's exposure history by hand or into a Pinellas-based computer system and GE's Corporate Health and Safety Record (HSR) system (Richards 1986).

Starting in mid-1978, the Plant began using the Landauer polycarbonate plastic dosimeter for 14-MeV neutrons, and continued to use photographic film processing for 2.5-MeV neutrons, X-ray, beta, and gamma exposures, and Landauer thermoluminescent dosimeter (TLD) rings for hand monitoring (Burkhart 1987b).

From October 1979 through September 1987, the Plant used dosimeters from Mound Laboratory for evaluating exposures to X-rays and 2-MeV average neutrons from the handling of sealed $^{238}PuO_2$ sources during the production of RTG units in Building 400, and continued to use the Landauer dosimetry discussed above for exposures from all other radiation sources, including 14-MeV neutrons. Problems related to the DOE Laboratory Accreditation Program (DOELAP) testing with the Mound dosimetry and the equivalent performance of Landauer neutron dosimetry led GEND to discontinue use of the Mound dosimetry in October 1987 (Burkhart 1987b). Beginning in 1990, earlier dosimetry technology was replaced with Landauer TLD dosimetry that was used until the end of nuclear development and testing operations in 1994. Table 6-2 summarizes the significant historical events for the dosimetry program at the Pinellas Plant.

Table 6-2. Pinellas Plant historical dosimetry events.

Date	Event	Reference
1957	In-plant processing of gamma and neutron film dosimeters initiated.	Burkhart 1987a
April 1957	New employee orientation in radiation safety offered.	Burkhart 1990
October 1957	Measured neutron dose rates at all test positions.	Burkhart 1990
November 1957	Measured neutron output of neutron generators, and was determined to be equivalent to 10 mrem/pulse at 1 in.	Burkhart 1990
December 1957	Sandia National Laboratories (SNL) asked to provide film badges. However, there is no indication that SNL ever provided any film badges for the Pinellas Plant.	Burkhart 1990
January 1960	Full-time Health Physics representative assigned to Area 108.	Burkhart 1990
November 1963	Began use of wrist badges in place of ring badges for limited number of employees.	Burkhart 1990
February 1965	GEXM memorandum comparing performance of two types of neutron badges and two types of gamma badges.[a]	Szedziewski 1965
Late 1969	Film badge fading study.	Author unknown 1969
January 1973	Memorandum on dose rate for stress test facility.	Holliday 1973
July 1974	Began using Landauer as source of film badges.	Ward 1974
April 1978	Memorandum on personnel neutron dosimetry recommending use of new Landauer neutron badge using polycarbonate plastic.	Holliday 1978
October 1979	Began using Mound neutron dosimeters.	Burkhart 1987b
1986	Landauer switched from reporting photon doses as exposures to reporting them as deep doses.	Yoder 2005
October 1986	Memorandum on estimated doses to GEND personnel handling unmarked neutron generator units.	Burkhart 1986
October 1987	End use of Mound neutron dosimeters.	Burkhart 1987b
October 1988	Memorandum on radiation dose rates from RTG heat sources.	Weaver 1988
April 1990	Changed from Landauer film to thermoluminescent dosimetry.	Hall 1989
1971–1993	Various determinations for doses from testing of sealed neutron generators.	GE 1971-1996
September 1994	Nuclear product development and testing end. Other radiation-related work did continue.	

a. The Pinellas Plant was the progeny of General Electric's X-ray Division in Milwaukee (GEXM). Because the radiological control programs for these two sites were closely linked and because the available information indicates that the Pinellas Plant managed the radiological programs at GEXM after its startup, the information in this evaluation is considered to be applicable to the Pinellas Plant dosimeters.

Attachment A contains examples of handwritten and computer records for 1960 to 1988. The forms used in 1960 were also used before 1960 and the forms used in 1988 were used until Pinellas ceased operations.

A Pinellas Plant health physicist reviewed the reports and evaluated and resolved unusual or inconsistent results. The health physicist could modify the reports, documenting all investigations and reasons for such modifications. These reports were placed in the worker's dosimetry file. The health physicist checked the printed version of the Landauer reports against the electronic version. Until 1990, workers who reported lost or stolen badges were assigned an exposure that was an average from their previous dose histories (GE 1990a).

If Landauer found that a badge exceeded 400 mrem whole body, 800 mrem skin, or 6,000 mrem extremity, it was required to call the responsible Pinellas health physicist (GE 1990a). Analysis of the available claimant records found no documentation that this reporting requirement was ever exceeded during the time Landauer provided dosimetry services to the Plant (1974 to 1994).

GENERAL ELECTRIC COMPANY
NEUTRON DEVICES DEPT
ENVIRONMENTAL HLTH
7887 BRYAN DAIRY RD
LARGO FL 33543

ACCOUNT NO. 70463

Participant ID number	Name	Social security number	Note (see reverse side)	Dosimeter type	Use	Radiation quality	Exposure to badge (millirems) for period(s) indicated below		Cumulative totals (millirems)						Adjustments	Sex	Birth date			Number badge reports		Inception date	
									Calendar quarter		Year to date		Permanent										
							Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow			MO	DA	YR	To date	Qtr	MO	YR
[PIR]	AREA MONITOR 183			E	1		M	M	M	M	M	M	M	M						11	1	11	
[PIR]	[PIR]	[PIR]		U	3			M		M		M		M						24	2	11	84
[PIR]	CONTROL			G	1		M	M	M	M	M	M	260	260						295	5	6	74
[PIR]	TLD CONTROL							M		M		M		M						101	3	2	79
[PIR]	LOAN			U	3			M		M		M		220						96	3	2	79
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	M	M						7	5	9	86
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	100	100		M				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	250	250		M				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	110	110		F				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	10	10						23	3	11	84
[PIR]	[PIR]	[PIR]		G	5			M		M		M		M						23	3	2	85
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	240	240		M				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	30	30	250	250		M				255	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	40	40	90	90		M				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	90	90		M				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	200	100		M				256	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	170	170		M				257	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	M	M	180	180		M				258	5	6	74
[PIR]	[PIR]	[PIR]		G	1		M	M	M	M	40	40	140	140		M				254	5	6	74

PIR = privacy information removed.

Figure 6-1. Regenerated example of a Landauer dosimetry report from the 1970s.

6.2.1.1 Performance Testing

Neutron Studies

Eastman Kodak nuclear emulsion Type A (NTA) film was used for neutron measurements and should be similar to the Landauer NTA dosimetry used at Pinellas after 1974 for the Type J dosimeter (Author unknown 1969; Gordon 2004). As stated in the Hanford Site, Idaho National Laboratory, and Nevada Test Site Occupational External Dose TBDs (ORAUT 2010a, 2007, and 2010b, respectively), NTA was basically the only common dosimeter method available to measure neutron dose in AEC facilities prior to the use of thermoluminescent dosimeters (TLD). The neutron spectra at Pinellas were known to be dominated by higher energy 14-MeV deuterium-tritium and 2.5 MeV deuterium-deuterium fusion neutrons due to the unique designs of the neutron generators. These higher-energy neutron fields tend to minimize errors from fading or energy response reported at the first AEC Neutron Dosimetry Workshop in 1969 which indicated that Savannah River Site calibration laboratory dose measurements made with NTA film were about one-half to one-fourth of those measured with other methods, including the neutron TLD (Vallario et al. 1969).

Typically, the dominant neutron exposure from nuclear weapon components at Pinellas was readily and reliably measured with NTA film dosimeters. For neutrons from RTG production, Pinellas initially continued with NTA film but changed to polycarbonate dosimeters beginning in June 1978. From October 1979 through September 1987, TLDs from Mound Laboratory were used for measuring neutron exposures from RTG production. From September 1987 through the end of RTG production, Mound Laboratory dosimeters were out phased with a Landauer Type R dosimeter arrangement (Burkhart 1987a).

Specific Pinellas Plant Studies

The NTA film badge neutron dosimeters used from 1957 through 1977 underwent track fading during use, causing a loss of information (Holliday 1978). At least for a period, the neutron dosimeters were made of Kodak Type A film (Author unknown1969). GEND established a factor of 3 to correct for track fading beginning in January 1970, based on a track fading study (Author unknown1969). The maximum errors associated with the use of this factor occurred when a worker received a majority of the neutron exposure at the beginning or the end of a dosimeter monitoring period. The assigned dose to a worker receiving a total exposure on the first day of a dosimeter period would be 20% of the true dose per week; while the dose assigned to a worker receiving a total exposure on the last day of the monitoring period would be 40% of the true dose for a monthly wear period (Author unknown1969). The Landauer polycarbonate badge that replaced these badges in May 1978 did not undergo track fading, so no correction factor was applied after May 1978 (Holliday 1978). The Landauer Type I dosimeter, which was used in the Type R dosimeter package, had a limited sensitivity to neutrons from the sealed PuO_2 sources in the RTG units; this was calculated to be 67% of the true dose by GEND health physics personnel.

In 1965, a dosimeter comparison study was performed. Part of the study compared the neutron dosimeters being processed at the Pinellas Plant to dosimeters obtained from and processed by Landauer. The study concluded that the neutron dosimeters processed by the Pinellas Plant were preferred over the Landauer dosimeters for neutron generator work (Szedziewski 1965).

6.2.1.2 Reports

An As-Low-As-Reasonably-Achievable (ALARA) Program report discussing occupational exposures was submitted to the manager of the Environmental Health and Safety Program. Attachment A contains examples of the reports kept by the Environmental Health and Safety Program and its radiation protection program from 1960 to 1988 for one claimant.

6.2.2 Dosimetry Technology

For the period of 1957–June 1974, no information regarding the specific design parameters for the film dosimeters used at the Pinellas Plant (e.g. film type, filters used, dosimeter holder design, etc…) could be found. There is limited documentation that indicates there might have been an early relationship with Nuclear-Chicago (GE 1957–1990), but that relationship might have only been with the Pinellas Plant's parent site (i.e., GE's X-ray Division in Milwaukee [GEXM]). Nothing has been found to confirm the use of the Nuclear-Chicago film dosimeters or dosimeter holders at the Pinellas Plant. For the period after June 1974, the dosimetry type and sources are well documented in the Landauer exposure reports. Table 6-3 summarizes the monitoring technique and describes suspected and known Plant dosimeters. Tables 6-10 and 6-11 in Section 6.4 summarize the limits of detection (LODs) of these dosimeters along with the maximum potential missed doses (NIOSH 2007).

Table 6-3. Dosimetry used at Pinellas Plant for external whole-body and extremity exposures[a].

Period	Dosimeter type	Dosimeter description
Whole body – beta-gamma dosimeters		
1957–Jun 1974	Photographic film (beta-gamma)	Nuclear-Chicago or similar film dosimeters processed in-house (Burkhart 1987b). Nuclear-Chicago film dosimeters for this era contained a single film packet. Three filters consisting of cadmium, aluminum, and lead were incorporated into fronts and backs of the film dosimeters for energy dependence (ORAU 2003). However, it could not be confirmed that these were the dosimeters used at the plant.
Jul 1974–Mar 1990	Landauer Type G[b,c] (beta-gamma)	The Type G dosimeter was a film emulsion package placed in standard Gardray holder/badge for monitoring beta, X-ray, and gamma exposures. It was insensitive to neutron radiation. Required in areas where Kr-85 was used. Required for radiation-generating equipment and accelerator operators. Gamma and X-ray: 30 keV to 20 MeV; beta: over 1.5 MeV.
Apr 1990–1997	Landauer Type Z/F[c] (beta-gamma)	The Type Z dosimeter was comprised of 3 TLD-700 chips for monitoring beta, X-ray and gamma exposures. It was insensitive to neutron radiation. After 1994, the Type Z dosimeter was renamed the Type F dosimeter.
Whole body – neutron and beta-gamma-neutron dosimeters		
1957– Jun 1974	NTA film (neutron only)	Nuclear-Chicago or similar film dosimeters that were equipped with Eastman/Kodak Nuclear Track Type A (NTA) film emulsions and processed in-house (Burkhart 1987b). Fast neutrons undergoing elastic collision with content of emulsion or cellulose acetate base material produced recoil protons, which were recorded as photographic tracks in the NTA film emulsion. Track density was a linear function of dose. Developed images exhibited tracks caused by neutrons, which could be viewed using appropriate imaging method (i.e., oil immersion) and 1000X-power microscope or projection capability.
Jul 1974–May 1978	Landauer Type P[b,c] (beta-gamma-neutron)	The Landauer Type P dosimeter appears to have been used in all areas with a potential for neutron exposures (Landauer 1974–1980). The Type P dosimeter was a combination beta-gamma and fast neutron dosimeter. The fast neutron dosimeter was an NTA film dosimeter and the beta-gamma dosimeter was likely a Landauer Type G film dosimeter.

Period	Dosimeter type	Dosimeter description
Jun 1978–1997	Landauer Type E[c] (neutron only)	The Landauer Type E neutron dosimeter was used in all areas at the Pinellas Plant until October 1979 when the site started to use the Mound dosimeters in areas with RTG operations. After October 1979, the Type E dosimeter was used only in the neutron generator areas at the Plant. The Type E dosimeter is a polycarbonate (Lexan®) neutron recoil track registration device used to monitor fast neutron interactions. Neutrak 144 has a dosimeter element for response to fast neutrons. Neutrak E1 has a polyethylene radiator over CR-39 chip that would monitor for fast neutrons; only Lexan® responded to neutrons by recording ionization damage caused by neutrons interacting with carbon and oxygen atoms, which leaves a track. It had uniform energy response from 3 to over 14 MeV with threshold of about 1 MeV (Weaver 1987). The Type E dosimeter was combined with the Type G dosimeter (and later with the Type Z/F dosimeter) (Weaver 1987, 1996). Workers were required to wear an E/G dosimeter combination when working around neutron generators. Accelerator operators were also required to wear an E/G dosimeter combination. An E/G dosimeter combination or a G dosimeter was required when working with calibration sources (Weaver 1987).
Oct 1979–Sep 1987[d]	Mound TLD (gamma-neutron)	The Mound TLD was used in areas with RTG operations (i.e., where PuO_2 was handled). It was used to measure exposures to the X-rays and 2-MeV average neutrons from the handling of the sealed PuO_2 sources during the production of RTG units in Building 400. This dosimeter utilized a Harshaw 8810 TLD package that included an albedo neutron monitoring capability. The Harshaw 8810 TLD package utilized a combination of TLD-600 and TLD-700 dosimeter chips, which were encased in a plastic holder made of Cycolac®.
Sep 1987[d]–Feb 1991	Landauer Type R/I[c] (beta-gamma-neutron)	The Landauer Type R dosimeter arrangement was used in areas with RTG operations (i.e., where PuO_2 was handled), and replaced the Mound TLD. The Type R dosimeter package consisted of a Type G dosimeter for measuring beta, X-ray, and gamma radiation and a Type I dosimeter for measuring neutron radiation. The Type I dosimeter combined a TLD albedo neutron monitor with a track recoil device (CR-39 [allyl diglycol carbonate]) that responds to proton recoil events. Neutron energy range was approximately 1×10^{-6} to 10 MeV. Albedo response to thermal neutron radiation was subtracted to yield fast neutron dose. The “Neutrak ER” has an albedo element with above-described elements. Qualitative relationship was derived to determine ratios of neutrons of various energies. When first used at the Pinellas Plant, the Type I dosimeters did not meet all DOELAP requirements during performance testing (Weaver 1991). After the Type G dosimeter was replaced by the Type Z dosimeter, the combined dosimeter unit was known as the Type I dosimeter. After production of RTGs was halted in October 1991, the Type R/I dosimeter was used only as an area monitor for the americium-beryllium (AmBe) source (Weaver 1991).

Period	Dosimeter type	Dosimeter description
		Wrist – beta-gamma dosimeters
Jul 1974–1990	Landauer Type G[c,e] (beta-gamma)	The Type G wrist dosimeter was a film emulsion package placed in a standard Gardray holder/badge for monitoring beta, X-ray, and gamma exposures. It was insensitive to neutron radiation. The Type G wrist dosimeter was used to monitor extremity doses in areas with RTG operations (i.e., where PuO_2 was handled) (Weaver 1987); extremity dosimetry was assigned in other areas as needed (Weaver 1996).
1991–1997	Landauer Type K[c] (beta-gamma)	The Landauer Type K wrist dosimeters assigned during this period utilized three TLD-100 chips.
		Finger ring – beta-gamma dosimeters
1957–1974	Photographic film (beta-gamma)	Nuclear-Chicago or similar film ring dosimeters processed in-house (Burkhart 1987b). Nuclear-Chicago film ring dosimeters contained a single film packet. Three filters consisting of cadmium, aluminum, and lead were incorporated into fronts and backs of the film dosimeters for energy dependence (ORAU 2003).
1975–1983	(unknown)	This analysis found no information regarding the type of ring dosimeters used during this period. If ring dosimeters were used during this period, they might have included the in-house film dosimeters or Landauer Type L ring dosimeters. Because the type of ring dosimeter that might have been used is uncertain, extremity doses based on ring dosimeters from this period will need to be assessed on a case-by-case basis.
About 1983[f]–1997	Landauer Type U[c] (beta-gamma)	The Landauer Type U ring dosimeters assigned during this period utilized one LiF TLD chip for monitoring beta (>1.5 MeV), X-ray, and gamma exposures. It was insensitive to neutron radiation. The Type U ring dosimeter was used to monitor extremity doses in areas with RTG operations (i.e., where PuO_2 was handled) (Weaver 1987); extremity dosimetry was assigned in other areas as needed (Weaver 1996).

a. Sources: Battelle 1956–2002; Burkhart 1987b; GE 1986–1988, 1990a,b; Greene 1985a; Hall 1989; Holliday 1978; Landauer 1974–1980, 2004; Ingle 1991; Weaver 1987, 1991, 1995, 1996; Passmore 2004; Gordon 2004.

b. A June 1974 memorandum indicates that the Pinellas Plant ordered Landauer Type J (beta-gamma) and Type K (beta-gamma and neutron) dosimeters (Burkhart 1987b); however, the actual dosimetry records indicate that Landauer Type G (beta-gamma) and Type P (beta-gamma and neutron) dosimeters were actually received and used (Landauer 1974–1980).

c. The use of the Landauer dosimeters is indicated by exposure type codes in the earlier years and use codes in the later years. The following are the dosimeter exposure type or use codes: 1 - whole body, 2 – skin/lens of eye, 3 - right finger, 4 – left finger, 5 – right wrist, 6 – left wrist, 7 – other extremity, 8 – other whole body, 9 - monitor.

d. Dual Mound and Landauer Type R neutron dosimeters were used to monitor RTG workers during the month of September 1987 (Burkhart 1987b).

e. A June 1974 memorandum indicates that the Pinellas Plant ordered Landauer Type M (beta-gamma) wrist dosimeters (Burkhart 1987b); however, the actual dosimetry records indicate that Landauer Type G (beta-gamma) wrist dosimeters were actually received and used (Landauer 1974–1980).

f. This analysis found no documentation that shows the start of use for the Landauer Type U finger ring dosimeters.

6.2.3 Dosimetry Calibration Practices

Pinellas conducted dosimetry calibration as part of its external dosimetry audit program. This type of performance testing occurred every 6 months using radiation sources with known strengths. Tests used the DOE *Standard for the Performance Testing of Personnel Dosimetry Systems* (DOE 1986) and American National Standards Institute *Personal Dosimetry Performance – Criteria for Performance* (ANSI 1993). Each test used approximately six to nine badges.

The photon calibration of the Landauer Type G dosimeters was performed by exposing the dosimeters to the Shepherd model 81-12 ^{137}Cs beam irradiator in Building 800 (a gamma check for 662-KeV photons). For beta calibration, the dosimeters were exposed by placing them on a bare uranium slab for exposure to the resulting radiation. A covering with a known density thickness was placed on the dosimeters to keep them free from uranium contamination (GE 1990a).

Calibration of the Landauer Type E polycarbonate dosimeters was performed by exposing them to a D-T fast neutron source with known source strength. The badges were placed on a Lexan® "jig" and set at a known distance from the source of neutrons (GE 1990a).

The Landauer Type R dosimeter, which consisted of a beta-gamma film dosimeter, an albedo neutron monitoring TLD, and a CR-39 neutron dosimeter, was placed on a water phantom and exposed to a Shepherd Model 149 calibrator equipped with an ^{241}Am-Be source. The phantom was level with (and at known distances from) the source on a moveable metal rack about 4 ft above the floor to minimize scattering effects (GE 1990a).

However, even though there is Pinellas Plant documentation showing such calibration studies occurred, the results of the studies and subsequent use in the radiation dosimetry program are not available.

Beginning in 1974, Landauer supplied all dosimetry badges and performed the necessary calibrations. Landauer used control film. The personnel monitoring reporting was normally in net exposure; the control film reading was deducted from the personnel film reading. If the control film appeared to have been exposed differently than the personnel packets, the densities on the personnel film were normalized to Landauer controls only and a nonminimal control reading was reported. A control packet reading was provided in arbitrary units, not necessarily in millirem. Minimal beta or soft X-ray skin dose readings were not reported until after a positive skin dose exposure was recorded. Ring badges were calibrated only for high-energy gamma (probably > 0.662 MeV) and high-energy beta (1.5 MeV) unless special arrangements were made with the Plant (Gordon 2004).

Further details of the dosimetry are listed in Tables 6-9 and 6-10 in Section 6.4. This includes the dosimeter types along with some dosimeter configuration and energy response characteristics. Table 6-9 lists the associated LODs and the maximum potential missed photon and electron doses. Table 6-10 lists the associated LODs and the maximum potential missed neutron doses. Even though the dosimeter designations or types changed, the LODs did not vary much over the operational history of the Pinellas Plant.

6.2.4 Workplace Radiation Fields

Potential sources for workplace radiation fields at Pinellas can be placed in two categories, radionuclides and machine-generated X-rays, neutrons, and electrons. The only open-area radiation fields to be routinely encountered by workers would be from the testing of neutron generators, the use of machine-generated X-rays, and areas where work was performed with the RTG heat sources.

Radionuclides were used directly in the manufacturing processes, manufacturing support, and various calibration sources. Table 6-4 lists radionuclides that would contribute to workplace radiation fields. The radionuclides applied in the manufacturing processes at the Pinellas Plant were kept in containers, in sealed sources, or in the process piping. Because most of the primary radiation from these sources (alphas and betas) would not penetrate the containers, sealed source encapsulation, or the process piping, and the workers would not be in close contact with the sources, the expected radiation fields would be very small. In the cases of tritium and ^{85}Kr, which were gases in the Pinellas processes, vent hoods or direct connections to ventilation exhaust systems quickly removed the gases from worker spaces. The largest calibration source was a 120-Ci ^{137}Cs source used in a Model 81-12 Beam Calibrator manufactured by J. L. Shepard and Associates (GE 1977). Three neutron sources were used at various times, two of which contained ^{239}Pu (1.7 Ci and 0.43 Ci) and an Am-Be source with 10 Ci of ^{241}Am. All three were removed from the Pinellas site by the end of 1991 (1979, 1990, and late 1991, respectively). All other calibration sources were in the millicurie and microcurie ranges and were sealed, and would not contribute to occupational doses (other than to workers who used the millicurie sources) (GE undated b, pp. 6-10).

There were also machine-generated radiation fields at the Pinellas Plant. X-rays and neutrons were generated from the neutron generators and X-rays were generated from other equipment listed in Table 2-1 of the *Technical Basis Document for the Pinellas Plant – Site Description* (ORAUT 2011b). For neutron generator tests, there was no shielding around the test area with the exception of the room walls. X-ray-generating equipment was designed to be in a shielded enclosure that, by certification, was below 0.5 mR/hr at 5 cm from the surface of the device. Most devices would have a lower radiation field. Shielding around the test area was added later at an unspecified time. There was also X-ray production from the tritium tube testing. This is implied by a description of exposures in a GE memo (Greene 1984a) and in a memo from Sandia National Laboratories describing X-ray generation from neutron tube testing (Brainard 1991). By calculation, it is assumed that X-ray dose was linear to the beam current of electrons and ions. The dose equivalent of X-rays produced was close to that of the neutron dose equivalent without any shielding of the tube present (Brainard 1991).

To support the production of RTGs, Pinellas health physicists measured RTG radiation fields to yield 3 mrem/hr gamma and 10 mrem/hr neutron at 10 cm (approximately 4 in.) from the surface of the device and measurements during a December 17, 1987, hazard review yielded 20 mrem/hr gamma and 60 mrem/hr neutron at contact. Both measurements were most likely from one RTG unit (GE 1987).

Another indicator of the expected radiation fields experienced by Pinellas workers comes from a review of the dosimetry records for the first 285 Pinellas Plant claims in the NIOSH Office of Compensation Analysis and Support Claims Tracking System (NOCTS) database (i.e., up through Claim No. [redacted]). Of the 285 claims, 60 workers had whole-body doses greater than 0.001 rem from all forms of radiation, with a cumulative dose of 16.823 person-rem. Of this cumulative dose, 7.152 person-rem (42.5%) was from external neutron exposures, 6.587 person-rem (39.2%) was from external beta/gamma exposures, and 3.085 person-rem (18.3%) was from internal tritium exposures. Of these 60 workers, 32 have lifetime whole-body doses greater than 0.100 rem, and 9 have Pinellas lifetime doses from all sources greater than 0.500 rem. Most of these doses were accumulated in a sporadic manner by receiving a dose over a fraction of a year and/or not having any recordable doses for several months or for years in some cases. Because a limited number of monitored employees received extremity dosimetry, only 5 of the 60 workers with external doses have recorded lifetime extremity doses. The extremity doses for those individuals were 0.020, 0.028, 0.056, 0.483, and 0.730 rem. The exposure histories in these 285 claims are supported by the annual radiation exposure summary reports compiled by the AEC from 1960 to 1973, which indicates that there were only two instances when a Pinellas Plant worker received more than 1.0 rem in a given year.

Table 6-4. Radionuclides contributing to workplace radiation fields.

			Energies and abundances of major radiations[a]			
Nuclide	**Source**	**Half-life**	**Alpha (MeV)**	**Average beta (keV)**	**Photon (keV)[b]**	**Neutron (MeV)**
Kr-85	Leak check source	10.72 yr	---	251.4 (99.6%)	514 (0.43%)	---
Cs-137	Calibration source	30.17 yr	---	156.8 (94.6%) 415.2 (5.4%)	661.6 (89.98% from decay of Ba-137m)	---
Am-241	Part of Am-Be sealed neutron source	432.2 yr	5.39 (1.4%) 5.44 (12.8%) 5.49 (85.2%)	---	26.3 (2.4%) 59.5 (35.9%)	Thermal neutrons by a ^{9}Be(α,n) reaction
DU metal powder for H-3 storage						
U-238	99.75% weight	4.47E9 yr	Not listed.	---	---	By weak spontaneous fission
U-235	0.25% weight	7.04E8 yr	Not listed.	---	109.1 (1.5%) 143.7 (10.5%) 163.4 (4.7%) 183.7 (54%) 202.1 (1.0%) 205.3 (4.7%)	By weak spontaneous fission
U-234	0.0005% weight	2.45E5 yr	Not listed.	---	---	By weak spontaneous fission
Radionuclide composition of sealed PuO_2 sources used for RTG units[c]						
Pu-238	80.2% weight	87.75 yr	5.46 (28.3%) 5.50 (71.6%)	---	---	By weak spontaneous fission and ^{18}O(α,n) reaction
Pu-239	15.9% weight	24,131 yr	5.10 (11.5%) 5.14 (15.1%) 5.16 (73.3%)	---	---	By weak spontaneous fission and ^{18}O(α,n) reaction
Pu-240	3.022% weight	6,569 yr	5.12 (26.4%) 5.17 (73.5%)	---	---	By weak spontaneous fission and ^{18}O(α,n) reaction
Pu-241	0.643% weight	14.4 yr	---	5.2 (100%)	---	---
Pu-242	0.132% weight	3.76E5 yr	4.87 (22.4%) 4.90 (78.0%)	---	---	By spontaneous fission and ^{18}O(α,n) reaction
U-234	0.140% weight	2.45E5 yr	4.72 (27.4%) 4.78 (72.4%)	---	---	By weak spontaneous fission and ^{18}O(α,n) reaction
Np-237	0.130% weight	2.14E6 yr	4.64 (6.2%) 4.66 (3.3%) 4.71 (1.0%) 4.77 (33.0%) 4.79 (47.0%) 4.80 (1.6%) 4.81 (2.5%) 4.87 (2.6%)	---	---	By weak spontaneous fission and ^{18}O(α,n) reaction
Am-241	0.0033% weight	432.2 yr	5.39 (1.4%) 5.44 (12.8%) 5.49 (85.2%)	---	26.3 (2.4%) 59.5 (35.9%)	By weak spontaneous fission and ^{18}O(α,n) reaction

a. Energy information from Kocher (1981); with the exception of Kr-85, radiation emissions with abundances less than 1.0% were not listed in this table; the alpha particles are not an external dose hazard and are only being listed in this table when they are a significant source of neutrons via an alpha-neutron reaction (α,n).

b. The characteristic K and L shell X-rays have not been included in this table because the encapsulation materials for the affected sources would have attenuated their emissions to an insignificant level.

c. Radionuclides that are present in quantities less than 0.001% by weight are not listed; the encapsulation material for these sources would have attenuated the photon emissions from the ≤ 60 keV photons to less than 1/20,000th of their original intensity; also, the photons emitted from the spontaneous fission reactions, alpha-neutron reactions, and decay of fission and activation products are not listed in this table.

6.2.4.1 Electron and Photon Exposures

The NIOSH Interactive RadioEpidemiological Program (IREP; NIOSH 2007) discusses three photon energy bands – below 30 keV, 30 to 250 keV, and above 250 keV. The principal source of photons to the greater number of Pinellas workers would have been the various X-ray generating devices due to the limited access by a small number of workers to direct contact with radionuclides that emit photons (^{85}Kr in the two leak detection systems, the one ^{137}Cs sealed source in a shielded calibration machine, DU in the tritium storage beds, and ^{238}PuO$_2$ RTG heat sources).

The X-ray machines would generate photon energies below 250 keV. Because the machines were shielded, those used probably have a range of energy settings; and because measurements of the photon energies on the outside of the shielding are not available, this analysis grouped this source of photons in the 30- to 250-keV energy interval, which should be favorable to claimants. Table 6-5 lists electron and photon energies and percentages for processes at the Pinellas Plant.

Table 6-5. Electron and photon radiation energies and percentages for Pinellas Plant processes.

Facility or location	Process type	Radiation type	IREP energy group	Percentage
Buildings 100, 200, 300, 400, Medical	Neutron generator production, quality assurance, and RTG production	Photon	30–250 keV	100
Building 100, Area 109	Product analysis (Radiflo® and X-ray)	Electron Photon	> 15 keV 30–250 keV > 250 keV	100 86 14
Building 800	Calibration and accelerator	Photon	30–250 keV	100

External electron exposures due to beta particles were unlikely. The predominant source of electron radiation at the Pinellas Plant was tritium, but this radionuclide emits a low-energy beta particle that averages only 5.7 keV. Because electrons below 15 keV do not have sufficient energy to penetrate the epidermal layer of the skin (NIOSH 2007), tritium is not considered an external radiation hazard. The only sources of electron radiation with sufficient energy to penetrate the skin are ^{85}Kr and ^{137}Cs. (Note: There was the use of DU beds for tritium processing, but the DU was in small metal cylinders that would have attenuated the beta component from the worker.) Several incidents occurred in which workers were exposed to ^{85}Kr, so potential exposures to electron radiation should be considered in the area where the two ^{85}Kr leak detection systems (Radiflo® and TracerFlo systems) were located. The ^{137}Cs was in a sealed source in a shielded cabinet in the concrete Building 800, so the probability of a worker receiving electron radiation exposures from ^{137}Cs was remote.

Electron radiation exposures were possible for X-ray diffraction and electron beam devices if containment of the beams was compromised. It is more likely that exposures from these devices would have been from X-rays or bremsstrahlung production and not from any free electron beam. The exposures, if diffuse, would have been monitored by film badge or TLD. Most unusual occurrences were documented and any likely penetrating or nonpenetrating exposures would have been addressed in personnel medical records.

6.2.4.2 Neutron Exposures

There were two distinct neutron sources at the Pinellas Plant – 2.5- and 14-MeV neutrons from the testing of neutron generators and 2-MeV average neutrons from the sealed plutonium sources in the RTGs. The locations of the operations producing neutrons include a small number of areas. However, personnel wore neutron dosimetry in other locations; Table 6-6 lists the locations where workers wore neutron dosimetry and the expected neutron source energies.

Table 6-6. Expected neutron radiation energies for Pinellas Plant processes.

Facility or location	**Process type**	**Neutron energy (MeV)**
107	Tube assembly	2-14
128	Tube test	2-14
131	Final test	2-14
132M	Fan room	2-14
182	Tube assembly	2-14
183	General development	2-14
184	Tube testing	2-14
191	CPE hood room	2-14
194	Engineering environmental testing	2-14
	Radioanalytical Laboratory	2-14
Building 200	Product QA testing	2-14
Building 300		2-14
Building 400	RTG assembly and testing	0-12
Building 800	Calibration and accelerator	2-14

The RTG PuO_2 heat source spectrum is illustrated in Figure 6-2 (Greene 1984b). The spectrum was probably obtained from the Mound Laboratory and was used to analyze the effectiveness of various Landauer Neutrak TLDs by the Pinellas health physics department (Burkhart 1987a). It was determined that the Landauer dosimeter responded to only about 67% of the dose equivalent for the RTG PuO_2 heat source spectrum.

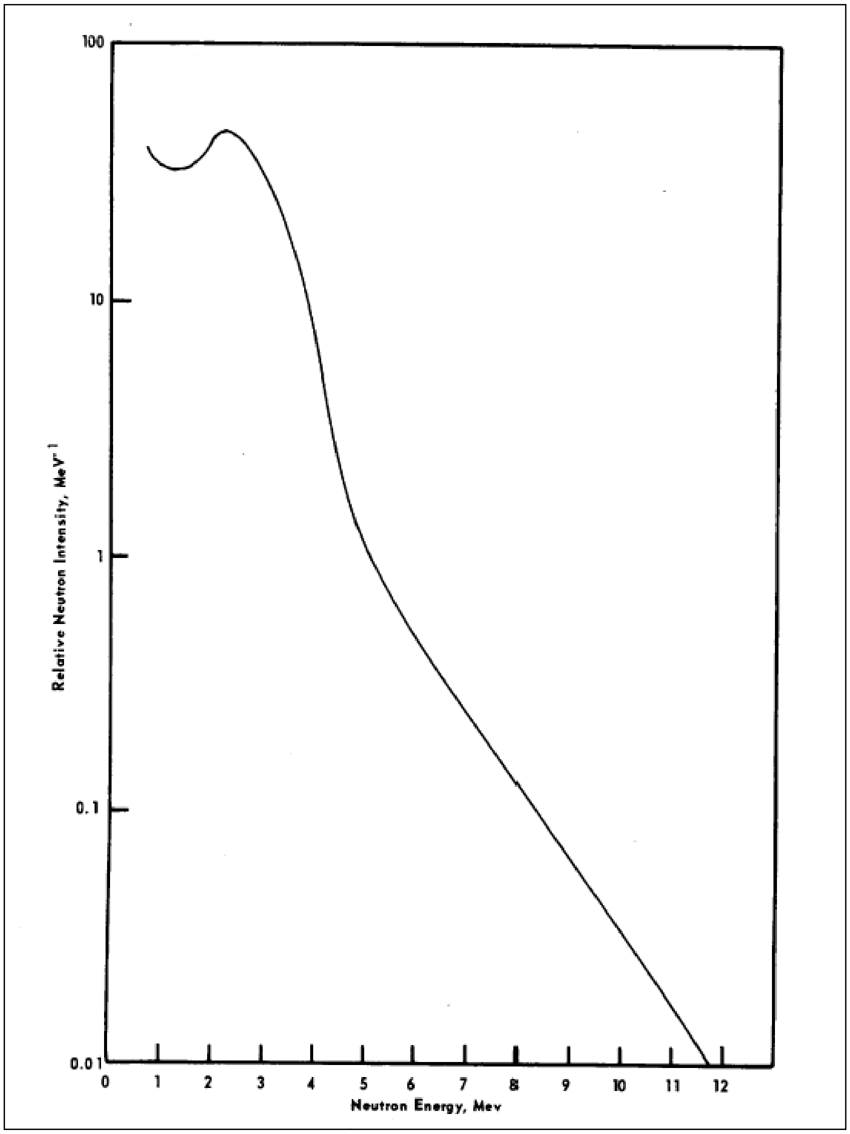

Figure 6-2. RTG plutonium source neutron energy spectrum – PuO_2 microspheres (Greene 1984b).

6.3 ADJUSTMENTS TO RECORDED DOSE

Adjustments to Pinellas Plant recorded doses are necessary to arrive at an accurate or favorable-to-claimant dose, considering the uncertainty associated primarily with the complex workplace radiation fields and exposure geometries. A key item for dose reconstructors to understand about the GEND radiation protection program is that for an individual lifetime dose [denoted as the Neutron Devices Department (NDD) lifetime dose in GEND files], the internal exposure from tritium was combined with the external exposure from neutrons, gamma rays, and X-rays. To reconstruct a claimant's lifetime dose properly, the dose reconstructor should separate the tritium dose from the rest of the external dose.

The recorded Pinellas doses show that there is not a consistent relationship between recorded neutron and photon doses for work performed in the neutron generator areas at the Plant. This lack of a true neutron-to-photon dose ratio can be attributed to the nature of the Pinellas processes, during which neutron generator testing occurred in open rooms that, combined with the short period of the neutron pulse, relatively open test structure, virtually no photons from the neutron generator, and relative low number of neutrons per test pulse (no significant quantities of activation products), would result in a corresponding photon dose. This result is supported in the individual dose records, which indicate that the timing of Pinellas personnel neutron and photon exposures varied greatly not only on a yearly but also on a monthly basis (a recorded value for 1 month and no recorded doses for the next several months). Thus, the assignment of a neutron-to-photon dose ratio to adjust for a missed neutron dose is not valid for the Pinellas Plant for neutron generators.

However, for RTG PuO_2 heat sources an approximate 3:1 neutron-to-photon ratio was measured based on neutron and photon exposure rates from the processing of the RTG PuO_2 heat sources as measured in 1987 (GE 1987b). Exposure rates measured at another time were 0.37 mR/hr neutron and 0.18 mR/hr gamma at 24 in. Actual dose equivalent received from removal and processing of 15 units for one worker (apparently the typical workload was 50 generators per month for perhaps three personnel) amounted to a 20.9-mrem neutron and 7.1-mrem gamma dose equivalents or approximately a 3:1 neutron-to-photon ratio (GE 1983). Because the RTG radioisotopic ratios and activities remained unchanged and the workstations and processes consistent, this ratio can also be considered a constant for RTG work conducted from 1975 to 1990.

6.3.1 Photon Dose Adjustments

With the exception of the Mound TLDs, no adjustments to photon doses are necessary for dose reconstruction.

6.3.1.1 Signal Fading Adjustments

Prior to July 1981, the Mound TLDs were subject to signal fading, which could amount to 25 to 30% of the stored signal fading during a period of 4 weeks (Crain 1981a). Beginning with the third quarter of 1981, the Mound TLDs were annealed before being packed into the dosimeter holders/badges to reduce the signal fading problem to a negligible level (Crain 1981a,b). As a result of this signal fading, the doses reported for the affected dosimeters were as little as 70% of the actual dose. To compensate for the signal fading, the Mound TLD results reported during the period from October 1979 through June 1981 should be multiplied by a signal fading correction factor of 1.43 (1/0.70). After June 1981, there was no significant signal fading for those dosimeters, and no corrections for signal fading are necessary.

6.3.2 Neutron Dose Adjustments

The following subsections provide the bases for the various neutron dose adjustments. The necessary neutron dose adjustments are summarized in Tables 6-7 and 6-8 below.

6.3.2.1 Radiation Weighting Factor Adjustments

The Pinellas Plant used a relative biological effectiveness (RBE) weighting factor of 10.0 when calculating the effective dose for 14-MeV neutrons (Holliday undated; MMSC 1994b, p. 249), which is equivalent to the ICRP Publication 60 neutron weighting factor for neutron energies from 2 to 14 MeV (ICRP 1991). Because the weighting factor value used by the Pinellas Plant is higher than other values that could have been used (such as those in NCRP 1971), the ICRP Publication 60 correction factor is unity for neutron exposures in the neutron generator areas.

The plutonium in the RTGs emits neutrons with an average energy of 2 MeV and an energy range of thermal to 12 MeV (Figure 6-2) (Burkhart 1987a). Based on the average neutron energy being 2 MeV, 50% of the neutrons were assumed to be in the 2- to 20-MeV neutron energy group and the remaining 50% of the neutrons were assumed to be in the neutron energy group of 0.1- to 2-MeV, which is typically the most favorable-to-claimant neutron energy group. The available GEND documentation does not describe any separate processing of the dosimetry when Landauer dosimeters were used to monitor exposures from RTG operations. Therefore, it was assumed that an RBE of 10 was applied to the neutron doses from RTG operations when Landauer dosimeters were used for the RTG operations (i.e., 1975–September 1979 and September 1987–February 1991). When the Mound dosimeters were used to monitor exposures from RTG operations (i.e., October 1979–September 1987), a single RBE value of 7 was applied to the Pinellas Plant doses reported by the Mound Laboratory (ORAUT 2004). Because the RBE value used for the Landauer dosimeters is uncertain and because the RBE used for the Mound dosimeters is likely more favorable to claimants than what was used for the Landauer dosimeters, the radiation weighting factor adjustments for all neutron energy groups and all periods of RTG operations should be based on an RBE value of 7.

A summary of the ICRP Publication 60 correction factors (ICRP 1991) for the Pinellas Plant's reported neutron doses is provided in Table 6-7.

Table 6-7. Neutron radiation energies and ICRP 60 correction factors.

Process Type	Neutron Energy Range	IREP Energy Group	Default Dose Fraction[a] (%)	ICRP 60/RBE Ratio[b]	ICRP 60 Correction Factor[c]
neutron generator operations	≤14 MeV	2-20 MeV	100%	10/10	1.00
RTG operations	0-2 MeV 2-12 MeV	0.1-2 MeV 2-20 MeV	50% 50%	20/7 10/7	1.43 0.71

a. Because no neutron dose values for the various neutron energies were available at the time of this assessment, the default dose fractions for the Pinellas Plant are actually just based on the expected neutron energy distributions.

b. The ICRP 60/RBE ratio is the appropriate radiation weighting factor in ICRP 60 (ICRP 1990) divided by the historical RBE value that was applied to the reported neutron doses.

c. The ICRP 60 correction factor is the ICRP 60/RBE ratio multiplied by the appropriate fraction/percentage for the neutron energy group.

6.3.2.2 Track Fading Adjustments

The NTA track film that was used at the Pinellas Plant from the start of operations in 1957 through June 1978 was susceptible to track fading. Track fading occurs between the time the tracks in the dosimeter were created and when the dosimeter film was analyzed. As this time interval increases, the amount of track fading increases.

A study was performed in 1969 to determine the amount of track fading on the NTA track film dosimeters that were used at the Pinellas Plant. Track fading was potentially significant because of the Plant's monthly dosimeter exchange frequency. The study determined that an average of 67% of the proton-recoil tracks had faded for a monthly dosimeter exchange. In other words, on average only 33% of the original tracks remained by the time the dosimeters were analyzed. The study recommended that a correction factor of 3 (i.e., 1/0.33) be incorporated into the dose calculations beginning in January 1970 to account for track fading (Author unknown1969). A 1974 memorandum from Landauer indicates that the correction factor of 3 was also being applied to the NTA film dosimeter results provided by Landauer for the period of July 1974 through May 1978 (Wheeler 1974).

Because there is no indication that the Pinellas Plant performed any track fading corrections to the reported neutron doses prior to 1970, the dose reconstructor should apply a track fading correction factor of 3.0 to the neutron doses reported for the years of 1957–1969. No track fading corrections need to be applied to the neutron doses reported after 1969, because the reported neutron doses have already been corrected.

6.3.2.3 Signal Fading Adjustments

Prior to July 1981, the Mound TLD was subject to signal fading, which could amount to 25% to 30% of the stored signal fading during a period of 4 weeks (Crain 1981a). Beginning with the third quarter of 1981, the Mound TLDs were annealed before being packed into the dosimeter holders/badges to reduce the signal fading problem to a negligible level (Crain 1981a,b). As a result of this signal fading, the doses reported for the affected dosimeters were as little as 70% of the actual dose. To compensate for the signal fading, the Mound TLD results reported during the period from October 1979 through June 1981 should be multiplied by a signal fading correction factor of 1.43 (1/0.70). After June 1981, there was no significant signal fading for those dosimeters, and no corrections for signal fading are necessary.

6.3.2.4 Neutron Energy Response Adjustments

Because of the higher neutron energies associated with the neutron generator production activities, the reported neutron doses for workers in the neutron generator portions of the Pinellas Plant do not need to be adjusted for the dosimeters' poor response to lower neutron energies. However, reported neutron doses for the Plant's RTG workers need to be adjusted because of the limitations of some of the dosimeter responses to the lower energy neutrons that were encountered in the RTG areas.

NTA film has a neutron energy response threshold of 0.5 MeV. Because some of the neutrons associated with the RTG PuO_2 heat sources had neutron energies below 0.5 MeV, the reported neutron doses from the start of Pinellas operation through June 1978 require a correction for poor energy response. Based on the neutron energy distribution information for the RTG PuO_2 heat sources (Burkhart 1987a), 6.4% of the neutrons were in the 0–1 MeV energy range and were assumed to not have been detected by the NTA film dosimeters. Therefore, a neutron energy response correction factor of 1.07 [1/(1-0.064)] should be applied to all NTA film dosimeter results to account for any under-reported neutron doses due to the NTS film dosimeter's energy response.

Because the Mound dosimeters utilized TLD chips that responded well to the neutron energies encountered by RTG workers, no adjustment for the neutron energy response of the Mound dosimeters is necessary (ORAUT 2004).

The GEND health physics group determined that the Neutrak ER portions of the Landauer Type R/I neutron dosimeter recorded only 67% of total neutron dose because of the dosimeter's poor energy response to low-energy neutrons from the RTG PuO_2 heat sources (Burkhart 1987a). In addition, there is no indication that the reported neutron doses for the RTG workers have been adjusted by the Pinellas Plant. Therefore, a neutron energy response correction factor of 1.49 (1/(0.67) would account for the under-reported neutron doses from the RTG PuO_2 heat sources.

Table 6-8. Summary of neutron dosimeter correction factors.[a]

Applicable period	Type of correction factor Track fading	 Signal fading	 Energy response	Total adjustment
Neutron generator operations (1957–1997)				
1957–1969	3.00	N/A	N/A	3.00
1970–1997	N/A	N/A	N/A	1.00
RTG operations (1975–1991)				
1975–Sep 1979	N/A	N/A	1.07	1.07
Oct 1979–Jun 1981	N/A	1.43	N/A	1.43
Jul 1981–Sep 1987	N/A	N/A	N/A	1.00
Oct 1987–Feb 1991	N/A	N/A	1.49	1.49

a. This summary includes all of the neutron dosimeter correction factors except the ICRP Publication 60 correction factors, which are already summarized in Table 6-7.

6.3.3 Electron Dose Adjustments

Electron doses were monitored but not routinely recorded. The primary source of electron exposures was from the use of two^{85}Kr leak detection systems (Radiflo® and TracerFlo systems) in Area 109 from about 1963 through 1994.

Beta dose monitoring for ^{85}Kr started before the DOELAP standard release, which used a calibration factor from a ^{90}Sr/^{90}Y source that tended to underestimate the dose from ^{85}Kr exposures. To compensate for the lower energy of ^{85}Kr in relation to that of ^{90}Sr/^{90}Y, a correction factor might have been used for the Pinellas Plant based on the more similar ^{204}Tl energy spectrum. Because it is not clear from the Plant records whether the ^{204}Tl energy calibration or equivalent was requested by Pinellas of Landauer or other vendors prior to 1986, a correction should be performed on the reported non-penetrating or electron doses prior to 1986 to ensure that the workers' doses are not underestimated. To compensate for the energy spectrum differences the reported nonpenetrating or electron doses should be multiplied by a correction factor of 3.5 for the years prior to 1986 (Poliziani 1985). From 1986 onwards, when DOELAP and National Voluntary Laboratory Accreditation Program standards included ^{204}Tl calibration criteria for ^{85}Kr exposures, it is not necessary to apply a correction factor.

6.4 MISSED DOSE

Missed external dose is the unrecorded or unmeasured external dose that is the result of either relatively high detection limits, short monitoring periods, high dosimeter exchange frequencies, or a combination of these three factors (NIOSH 2007). Missed doses are applicable to the Pinellas Plant workers that were monitored for external dose and had one or more reported dosimeter readings that were less than half the LOD for the dosimeter. Missed dose is primarily estimated based on dosimeter results, where the number of zero or < LOD/2 values for a given year is multiplied by the LOD/2 value for the dosimeters used during that year (NIOSH 2007).

At the Pinellas Plant, electron, photon, and neutron doses were possible. However, electron doses, including missed electron doses, were unlikely, as discussed in Section 6.2.4.1. Based on the available information for the Pinellas Plant, chronic external exposures to electrons did not occur and acute external exposures to electrons were unlikely. Therefore, missed electron doses do not normally need to be assessed for Pinellas Plant workers.

Tables 6-9, 6-10, and 6-11 summarize the dosimetry parameters to be used for calculating missed doses for Pinellas Plant workers.

Table 6-9. Whole-body beta-gamma dosimetry missed doses.[a]

Dosimeter type	Period of use	LOD (rem)	Exchange frequency	Maximum annual missed dose (rem)[b]
Whole-body dosimeters for neutron generator operations (1957–1997)				
Photographic film	1957–Jun 1974	0.040 photons[c] 0.040 electrons[c]	Monthly	0.240 photons 0.240 electrons
Landauer Type G/P[d]	Jul 1974–Apr 1990	0.010 photons 0.040 electrons	Monthly (1974–1989)	0.060 photons (monthly) 0.240 electrons (monthly)
			Quarterly (after 1989)	0.020 photons (quarterly) 0.080 electrons (quarterly)
Landauer Type Z/F[e]	May 1990–1997	0.010 photons 0.040 electrons	Quarterly	0.020 photons 0.080 electrons
Whole-body dosimeters for RTG operations (1975–1991)				
Landauer Type G/P[d]	1975–Sep 1979	0.010 photons 0.040 electrons	Monthly	0.060 photons 0.240 electrons
Mound TLD	Oct 1979–Sep 1987[f]	0.020 photons[g]	Monthly	0.120 photons
Landauer Type R/I	Oct 1987[f]–Feb 1991	0.010 photons 0.040 electrons	Monthly (1987–1989)	0.060 photons (monthly) 0.240 electrons (monthly)
			Quarterly (after 1989)	0.020 photons (quarterly) 0.080 electrons (quarterly)

a. Some of the beta-gamma dosimeters listed in this table included a component for monitoring neutron exposures; however, only the beta-gamma components of those dosimeters are addressed in this table.

b. The maximum annual missed dose assignments are calculated by multiplying half of the dosimeter's LOD value by the maximum number of dosimeters exchanged in a given year (NIOSH 2007).

c. Estimated LODs for commonly used photon dosimetry (ORAUT 2006b).

d. The Landauer Type P dosimeter was a beta-gamma-neutron dosimeter that likely utilized a Type G dosimeter or equivalent for its beta-gamma component.

e. After 1994, the Landauer Type Z dosimeter was renamed the Type F dosimeter.

f. Dual Mound and Landauer Type R neutron dosimeters were actually used to monitor RTG workers during the month of September in 1987 (Burkhart 1987b). Because it is uncertain which dosimeters were used for the reported doses, the dosimeter with the most favorable-to-claimant LOD values was used and the period of use date has been adjusted to reflect that.

g. The LODs for the Mound dosimeters are based on the site-specific information provided for the Mound Site (ORAUT 2004).

Table 6-10. Whole-body neutron dosimetry missed doses.[a]

Dosimeter type	Period of use	LOD (rem)	Exchange frequency	Maximum annual missed dose (rem)[b]
Whole-body dosimeters for neutron generator operations (1957–1997)				
NTA film	1957–Jun 1974	0.050 neutrons[c]	Monthly	0.300 neutrons
Landauer Type P[d]	Jul 1974–May 1978	0.040 neutrons[e]	Monthly	0.240 neutrons
Landauer Type E	Jun 1978–1997	0.020 neutrons[e]	Monthly (1974–1989)	0.120 neutrons (monthly)
			Quarterly (after 1989)	0.040 neutrons (quarterly)
Whole-body dosimeters for RTG operations (1975–1991)				
Landauer Type P[d]	1975–Sep 1979	0.040 neutrons[e]	Monthly	0.240 neutrons
Mound TLD	Oct 1979–Aug 1987[f]	0.010 neutrons[g]	Monthly	0.060 neutrons
Landauer Type R/I	Sep 1987[f]–Feb 1991	0.020 neutrons[e]	Monthly (1987–1989)	0.120 neutrons (monthly)
			Quarterly (after 1989)	0.040 neutrons (quarterly)

a. Some of the neutron dosimeters listed in this table included a component for monitoring beta-gamma exposures; however, only the neutron components of those dosimeters are addressed in this table.

b. The maximum annual missed dose assignments are calculated by multiplying half of the dosimeter's LOD value by the maximum number of dosimeters exchanged in a given year (NIOSH 2007).

c. NTA film LOD value based on Wilson et al. (1990).

d. The Landauer Type P dosimeter was a beta-gamma-neutron dosimeter that utilized NTA film for its neutron component.

e. The LOD for this Landauer NTA film dosimeter is based on specifications obtained from Passmore (2004).

f. Dual Mound and Landauer Type R neutron dosimeters were actually used to monitor RTG workers during September 1987 (Burkhart 1987b). Because it is uncertain which dosimeters were used for the reported doses, the dosimeter with the most favorable-to-claimant LOD values was used and the period of use date has been adjusted to reflect that.

g. The LODs for the Mound dosimeters are based on the site-specific information provided for the Mound Site (ORAUT 2004).

Table 6-11. Extremity beta-gamma dosimetry missed doses.

Dosimeter type	Period of use	LOD (rem)	Exchange frequency	Maximum annual missed dose (rem)[a]
Wrist dosimeters				
Photographic film	1957–Jun 1974	0.040 photons[b] 0.040 electrons[b]	Monthly	0.240 photons 0.240 electrons
Landauer Type G	Jul 1974–1990	0.010 photons 0.040 electrons	Monthly (1974–1989)	0.060 photons (monthly) 0.240 electrons (monthly)
			Quarterly (after 1989)	0.020 photons (quarterly) 0.080 electrons (quarterly)
Landauer Type K	1991–1997	0.010 photons 0.040 electrons	Quarterly	0.020 photons 0.080 electrons
Finger ring dosimeters				
Photographic film	1957–Jun 1974	0.040 photons[b] 0.040 electrons[b]	Monthly	0.240 photons 0.240 electrons
Unknown[c]	Jul 1974–1982			
Landauer Type U	About 1983[d]–1997	0.030 photons 0.040 electrons	Monthly (1974–1989)	0.180 photons (monthly) 0.240 electrons (monthly)
			Quarterly (after 1989)	0.030 photons (quarterly) 0.080 electrons (quarterly)

a. The maximum annual missed dose assignments are calculated by multiplying half of the dosimeter's LOD value by the maximum number of dosimeters exchanged in a given year (NIOSH 2007).

b. Estimated LODs for commonly used photon dosimetry (ORAUT 2006b).

c. Because the type of ring dosimetry used during this period was unknown at the time of this analysis, the assessment of any ring dosimeter results during this period will need to be handled on a case-by-case basis.

d. This is an estimated date because this analysis found no documentation that shows the start of use for the Landauer Type U dosimeter.

6.5 UNMONITORED DOSE

6.5.1 Unmonitored Workers

The majority of the work performed at the Pinellas Plant did not involve exposures to external sources of radiation, which explains why a significant number of the workers were not monitored for external dose. Based on the review of the available dosimetry data, employees with any significant potential for external dose exposure appear to have been routinely monitored, as evidenced by the large number of monitored individuals that routinely had doses below the reporting levels. Therefore, it is reasonable to assume that unmonitored workers received less dose than monitored workers at the Pinellas Plant.

For the periods in which any Pinellas Plant worker was not monitored for external dose, an annual unmonitored external dose assignment of 100 mrem should be assigned. For unmonitored periods that are less than 1 year in duration, the unmonitored dose assignment should be prorated, unless doses are being overestimated. For Plant workers who were likely exposed only to the onsite ambient levels of radiation, this more favorable-to-claimant unmonitored dose is assigned in lieu of the onsite ambient doses provided in the site's technical basis document on occupational environmental dose (ORAUT 2011c), for the reasons provided in the basis for the unmonitored external dose assignment. The basis for this unmonitored external dose assignment is in Attachment B of this document. In addition, the unmonitored external dose assignment should be assigned only as 100% 30- to 250-keV photons, for the reasons provided in Attachment B.

6.5.2 Workers Whose Dosimetry Records Are Missing

DOE has not been able to find the dosimetry records for a significant number of the Pinellas Plant workers. This situation was identified by comparing the DOE responses found in the claim files with the dosimetry records contained in ORAUT's Site Research Database (SRDB). For a number of claims, DOE has indicated that no records were found, whereas NIOSH has located full or partial sets of dosimetry records for those claims in its SRBD. As of the date of this document, DOE has not acknowledged that any dosimetry records for Pinellas Plant workers have been lost.

Because a monitored Pinellas Plant worker had a higher potential to receive external dose than an unmonitored worker, special considerations need to be made for workers whose dosimetry records are missing.

- In the instances where sufficient records are found in the SRDB, which are identified as Personnel Exposure files in the claim files, no special considerations need to be made and the other sections of this document can be used to assess the worker's external doses.

- In instances where there is only an indication that a worker was monitored for dose (e.g. records of annual whole-body doses found for some years; see note below), the worker's job description should be carefully evaluated to determine if the worker was likely monitored for neutron doses and/or photon doses. The appropriate annual missed doses should be assigned along with the annual unmonitored external dose assignment prescribed in Section 6.5.1, because missed doses were not accounted for in the unmonitored dose assignment for reasons indicated in Attachment B. For overestimating doses, the annual missed doses can be assigned based on the maximum zeros approach (the maximum dosimeters exchanged per year approach). For a reasonable, yet likely favorable-to-claimant estimate of a worker's missed doses, the annual missed doses should be based on the maximum potential number of dosimeter exchanges within a year minus 1 to account for the unmonitored dose assignment as being a single positive dosimeter reading.

  Note: When records consisting of only annual whole-body doses are found for some years, the reported doses could consist of external photon doses, external neutron doses, internal tritium doses, or any combination of these three types of dose. However, the available information for the Pinellas Plant indicates that neutron dose monitoring was always performed in conjunction with photon dose monitoring. Because the reported whole-body doses could consist of only internal tritium doses, the dose reconstructor needs to carefully evaluate the employment information for the worker to determine what type of dose monitoring was most likely performed. In the event that the type of dose monitoring cannot be determined, the default assumption is that external photon and internal tritium monitoring were performed, because these are the two most common types of monitoring that were performed at the Plant.

6.6 UNCERTAINTY

When a reported external dose is based on a single measurement, the uncertainty associated with that individual measurement needs to be accounted for in the assigned dose. In contrast to individual dose measurements, the uncertainty associated with external doses based on multiple measurements for the same period has already been accounted for in the dose assignment. An example of this is unmonitored dose assignments, which are typically based on either average or upper bound annual doses for a population of worker doses. As a result, this section only addresses how the uncertainties for individual external dose measurements should be assessed.

6.6.1 Beta-Gamma Dosimeter Uncertainty

For film dosimeters, the LODs that are quoted in the literature range from about 30 to 50 mrem for electron and photon irradiation (Morgan 1961). These are not the expected uncertainties at larger electron and photon dose readings. For example, it was possible to read a photon dose of 100 mrem to within ±15 mrem (±15%) if the exposure involved photons with energies between several hundred keV and several MeV (Morgan 1961). If the exposure involved photons with energies less than several hundred keV, the uncertainty was at least twice that for the more energetic photons (Morgan 1961). Therefore, the standard error in the recorded film dosimeter doses from photons of any energy is estimated to be ±30%. The standard error for the recorded dose from electron irradiation was essentially the same as that for photon irradiation, but when an unknown mixture of electron and photon irradiation was involved, the standard error for the dose from beta irradiation was somewhat larger than ±30% (Morgan 1961). Therefore, the standard error in the recorded film dosimeter doses from >15 keV electrons is estimated to be ±30% for a known mixture of photon and electron irradiation, and higher if the mixture is unknown.

For TLDs, the uncertainty is generally lower than the uncertainty for film dosimeter results; however, the uncertainty is still somewhat dependent on the measured dose (NIOSH 2007). Based on that observation, the uncertainty associated with the Pinellas Plant's recorded electron and photon doses from TLDs will be assumed to be ±30%, which is potentially favorable to claimants for some reported dose values.

6.6.2 Neutron Dosimeter Uncertainty

The NTA film technology used to measure neutron doses at the Pinellas Plant was similar to the technology used at other AEC/DOE facilities. Based on a review of the available information for such facilities, a reasonable uncertainty for neutron dose measurements performed using NTA film dosimeters is ±50%.

For the Landauer Type E neutron dosimeters, which were a polycarbonate (Lexan®) dosimeter, the sensitivity to fast neutron radiation was reported in 1978 as 30 ± 15 mrem (±50%) (Holliday 1978). It was also verified that the uncertainties of the dose determinations decrease as exposures increase (Holliday 1978). Therefore, a reasonable uncertainty for neutron dose measurements performed using the Landauer Type E dosimeters is ±50%.

For the Mound TLDs, an uncertainty of ±30% should be applied, based on the site-specific information for the Mound Site (ORAUT 2004).

For the Landauer Type R/I neutron dosimeters, an uncertainty of ±30% should be considered reasonable and likely favorable to claimants, based on a review of the available information for other AEC/DOE facilities.

6.7 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

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GLOSSARY

absorbed dose, D

Amount of energy (ergs or joules) deposited in a substance by ionizing radiation per unit mass (grams or kilograms) of the substance and measured in units of rads or grays. See *dose*.

accreditation

In relation to this document, recognition that a dosimeter system has passed the performance criteria of the DOE Laboratory Accreditation Program (DOELAP) standard (DOE 1986) in specified irradiation categories.

accuracy

The characteristics of an analysis or determination that ensures that both the bias and precision of the resultant quantity will remain within the specified limits.

albedo dosimeter

Thermoluminescent dosimeter that measures the thermal, intermediate, and fast neutrons scattered and moderated by the body or a phantom from an incident fast neutron flux.

alpha radiation

Positively charged particle emitted from the nuclei of some radioactive elements. An alpha particle consists of two neutrons and two protons (a helium nucleus) and has an electrostatic charge of +2.

backscatter

Reflection or refraction of radiation at angles over 90 degrees from its original direction.

beta particle

See *beta radiation*.

beta radiation

Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

curie (Ci)

Traditional unit of radioactivity equal to 37 billion (3.7×10^{10}) becquerels, which is approximately equal to the activity of 1 gram of pure ^{226}Ra.

densitometer

Instrument that uses a photoelectric cell to measure the transition of light through developed X-ray film to determine the optical density.

DOE Laboratory Accreditation Program (DOELAP)

Program for accreditation by DOE of DOE site personnel dosimetry and radiobioassay programs based on performance testing and the evaluation of associated quality assurance, records, and calibration programs.

dose

In general, the specific amount of energy from ionizing radiation that is absorbed per unit of mass. Effective and equivalent doses are in units of rem or sievert; other types of dose are in units of roentgens, rads, reps, or grays.

dose equivalent (H)

In units of rem or sievert, product of absorbed dose in tissue multiplied by a weighting factor and sometimes by other modifying factors to account for the potential for a biological effect from the absorbed dose. See *dose*.

dose equivalent index

Historical measure for neutron source calibration defined by the International Commission on Radiation Units and Measurements as the sum of the maximum dose equivalents delivered within a sphere at any depth for the respective neutron energies even though the maximum dose occurred at different depths and discounting the outer 0.07-millimeter-thick shell. Also called unrestricted dose equivalent index.

dosimeter

Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual. See *albedo dosimeter*, *film dosimeter*, *neutron film dosimeter*, and *thermoluminescent dosimeter*.

dosimetry system

System for assessment of received radiation dose. This includes the fabrication, assignment, and processing of external dosimeters, and/or the collection and analysis of bioassay samples, and the interpretation and documentation of the results.

electron radiation

See *beta radiation*.

error

Difference between the correct, true, or conventionally accepted value and the measured or estimated value. Sometimes used to mean estimated uncertainty. See *accuracy* and *uncertainty*.

exchange period (frequency)

Period (weekly, biweekly, monthly, etc.) for routine exchange of dosimeters. Also called exchange frequency.

exposure

(1) In general, the act of being exposed to ionizing radiation. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens.

extremities

The portion of the arm from and including the elbow through the fingertips and the portion of the leg from and including the knee and patella through the toes.

fast neutron

Neutron with energy equal to or greater than 10 kiloelectron-volts. This type of neutron causes fission in some isotopes (e.g., ^{238}U, ^{239}Pu). See *intermediate neutron* and *slow neutron*.

favorable to claimants

In relation to dose reconstruction for probability of causation analysis, having the property of ensuring that there is no underestimation of potential dose, which often means the assumption of a value that indicates a higher dose than is likely to have actually occurred in the absence of more accurate information. See *probability of causation*.

film

In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*.

film dosimeter

Package of film for measurement of ionizing radiation exposure for personnel monitoring purposes. A film dosimeter can contain two or three films of different sensitivities, and it can contain one or more filters that shield parts of the film from certain types of radiation. When developed, the film has an image caused by radiation measurable with an optical densitometer. Also called film badge.

filter

Material used in a dosimeter to adjust radiation response to provide an improved tissue equivalent or dose response.

gamma radiation

Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

intermediate neutron

Neutron with energy between 0.5 electron-volts and 10 kiloelectron-volts. See *fast neutron* and *slow neutron*.

ionizing radiation

Radiation of high enough energy to remove an electron from a struck atom and leave behind a positively charged ion. High enough doses of ionizing radiation can cause cellular damage. Ionizing particles include alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, photoelectrons, Compton electrons, positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons. See *alpha radiation*, *beta radiation*, *gamma radiation*, *neutron radiation*, *photon radiation*, and *X-ray radiation*.

isotope

One of two or more atoms of a particular element that have the same number of protons (atomic number) but different numbers of neutrons in their nuclei (e.g., ^{234}U, ^{235}U, and ^{238}U). Isotopes have very nearly the same chemical properties.

kilo-electron volt (keV)

Unit of particle energy equal to 1,000 (1×10^3) electron-volts.

luminescence

Emission of light from a material as a result of some excitation. See *thermoluminescence*.

limit of detection (LOD)

Minimum level at which a particular device can detect and quantify exposure or radiation. Also called lower limit of detection and detection limit or level.

megaelectron-volt (MeV)

Unit of particle energy equal to 1 million (1×10^6) electron-volts.

monitoring

Periodic or continuous determination of the presence or amount of ionizing radiation or radioactive contamination in air, surface water, groundwater, soil, sediment, equipment surfaces, or personnel (for example, bioassay or alpha scans). In relation to personnel, monitoring includes internal and external dosimetry including interpretation of the measurements.

neutron (n)

Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen.

neutron film dosimeter

Film dosimeter with a nuclear track emulsion, type A, film packet.

neutron radiation

Radiation that consists of free neutrons unattached to other subatomic particles emitted from a decaying radionuclide. Neutron radiation can cause further fission in fissionable material such as the chain reactions in nuclear reactors, and nonradioactive nuclides can become radioactive by absorbing free neutrons. See *neutron*.

personal dose equivalent [$H_p(d)$]

Dose equivalent in units of rem or sievert in soft tissue below a specified point on the body at an appropriate depth d. The depths selected for personal dosimetry are 0.07 millimeters (7 milligrams per square centimeter) and 10 millimeters (1,000 milligrams per square centimeter), respectively, for the skin (shallow) and whole-body (deep) doses. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively. The International Commission on Radiological Measurement and Units recommended $H_p(d)$ in 1993 as dose quantity for radiological protection.

photon

Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

photon radiation

Electromagnetic radiation that consists of quanta of energy (photons) from radiofrequency waves to gamma rays.

probability of causation (POC)

For purposes of dose reconstruction for the Energy Employees Occupational Illness Compensation Program Act, the percent likelihood, at the 99th percentile, that a worker incurred a particular cancer from occupational exposure to radiation.

quality factor, Q

Principal modifying factor (which depends on the collision stopping power for charged particles) that is employed to derive dose equivalent from absorbed dose. The quality factor multiplied by the absorbed dose yields the dose equivalent. See *dose* and *relative biological effectiveness*.

rad

Traditional unit for expressing absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium. A dose of 1 rad is equivalent to the absorption of 100 ergs per gram (0.01 joules per kilogram) of absorbing tissue. The rad has been replaced by the gray in the International System of Units (100 rads = 1 gray). The word derives from radiation absorbed dose.

radiation

Subatomic particles and electromagnetic rays (photons) with kinetic energy that interact with matter through various mechanisms that involve energy transfer.

radioactivity

Property possessed by some elements (e.g., uranium) or isotopes (e.g., ^{14}C) of spontaneously emitting energetic particles (electrons or alpha particles) by the disintegration of their atomic nuclei.

radioisotopically-powered thermoelectric generator (RTG)

Generator that obtains its power from passive (natural) radioactive decay using thermocouples to convert the heat of decay into electricity.

random error

When a given measurement is repeated and the values do not agree exactly. The causes of the disagreement between the values must also be the causes of their differences from the true value. See *systematic error*.

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

roentgen

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to 2.58×10^{-4} coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0°C and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

scattering

Change in direction of radiation by refraction or reflection, often accompanied by a decrease in radiation due to absorption by the refracting or reflecting material.

shallow dose equivalent

Dose equivalent in units of rem or sievert at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

shielding

Material or obstruction that absorbs ionizing radiation and tends to protect personnel or materials from its effects.

skin dose

See *shallow dose equivalent*.

systematic error

When a given measurement is repeated and the values differ from the true value by the same amount. See *random error*.

thermal neutron

Neutron in thermal equilibrium with its surroundings having an average energy of 0.025 electron-volts.

thermoluminescence

Property that causes a material to emit light as a result of heat.

thermoluminescent dosimeter (TLD)

Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated by radiation, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose.

tissue equivalent

Substance with response to radiation equivalent to tissue. A tissue-equivalent response is an important consideration in the design and fabrication of radiation measuring instruments and dosimeters.

U.S. Atomic Energy Commission (AEC)

Federal agency created in 1946 to assume the responsibilities of the Manhattan Engineer District (nuclear weapons) and to manage the development, use, and control of nuclear energy for military and civilian applications. The U.S. Energy Research and Development Administration and the U.S. Nuclear Regulatory Commission assumed separate duties from the AEC in 1974. The U.S. Department of Energy succeeded the U.S. Energy Research and Development Administration in 1979.

uncertainty

Standard deviation of the mean of a set of measurements. The standard error reduces to the standard deviation of the measurement when there is only one determination. See *accuracy* and *error*. Also called standard error.

whole-body dose

Dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder and commonly defined as the absorbed dose at a tissue depth of 10 millimeters (1,000 milligrams per square centimeter). Also called penetrating dose. See *dose*.

X-ray

See *X-ray radiation*.

X-ray radiation

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

ATTACHMENT A
EXAMPLES OF PINELLAS PLANT EXPOSURE RECORDS
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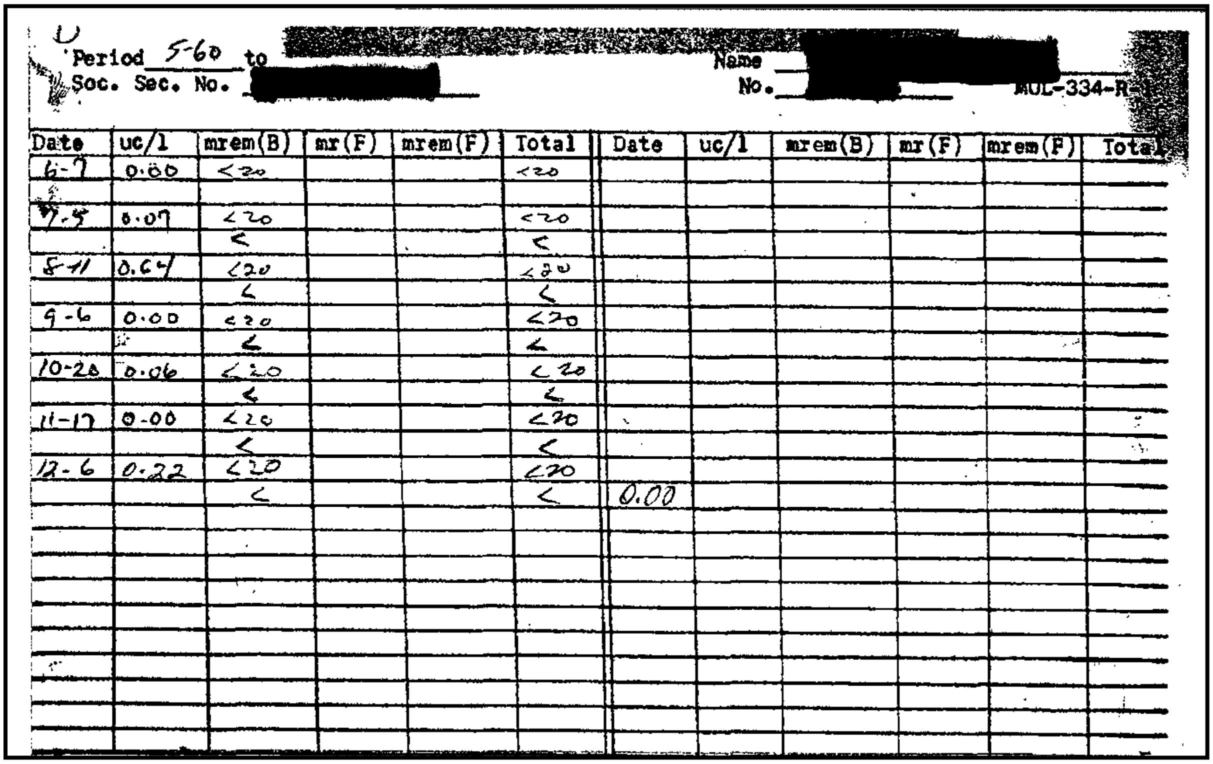

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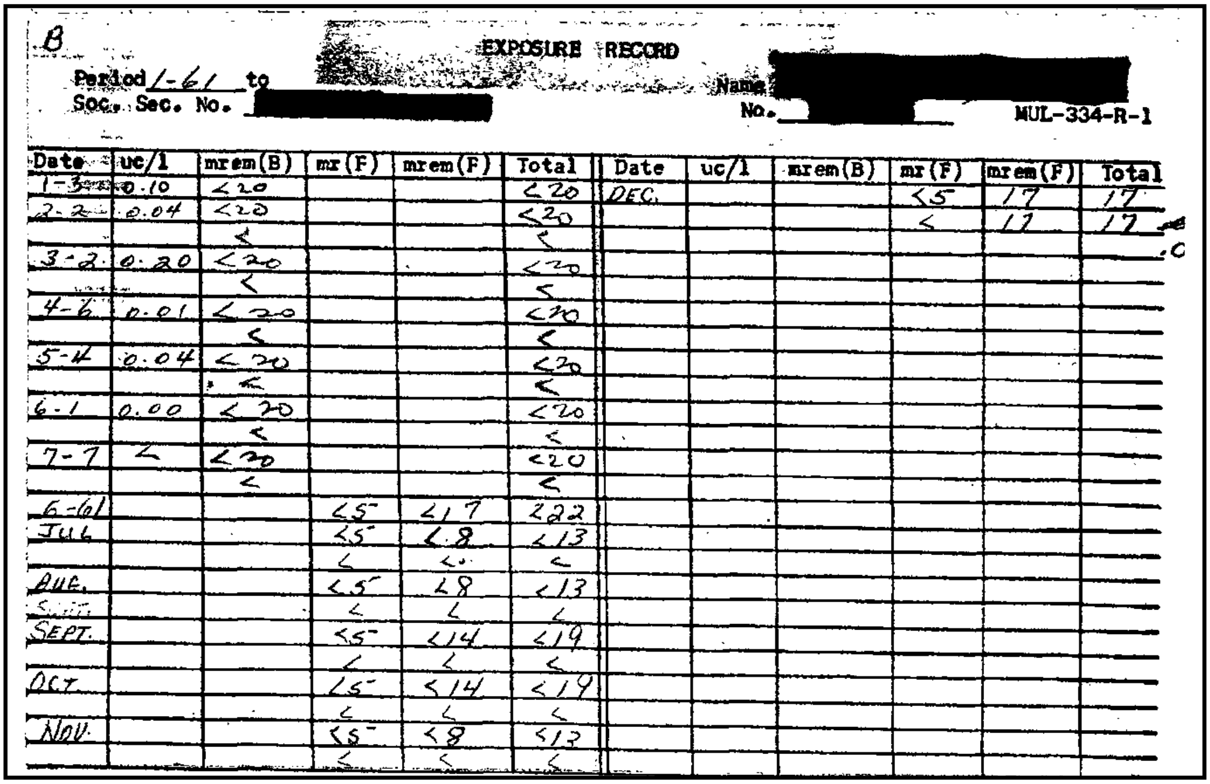
Soc. Sec. No. [redacted]

Name [redacted]
No. [redacted]
MUL-334-R-1

Date	uc/l	mrem(B)	mr(F)	mrem(F)	Total	Date	uc/l	mrem(B)	mr(F)	mrem(F)	Total
6-7	0.00	<20			<20						
7-5	0.07	<20			<20						
		<			<						
8-11	0.64	<20			<20						
		<			<						
9-6	0.00	<20			<20						
		<			<						
10-20	0.06	<20			<20						
		<			<						
11-17	0.00	<20			<20						
		<			<						
12-6	0.22	<20			<20						
		<			<	0.00					



B

EXPOSURE RECORD

Period 1-61 to
Soc. Sec. No. [redacted]

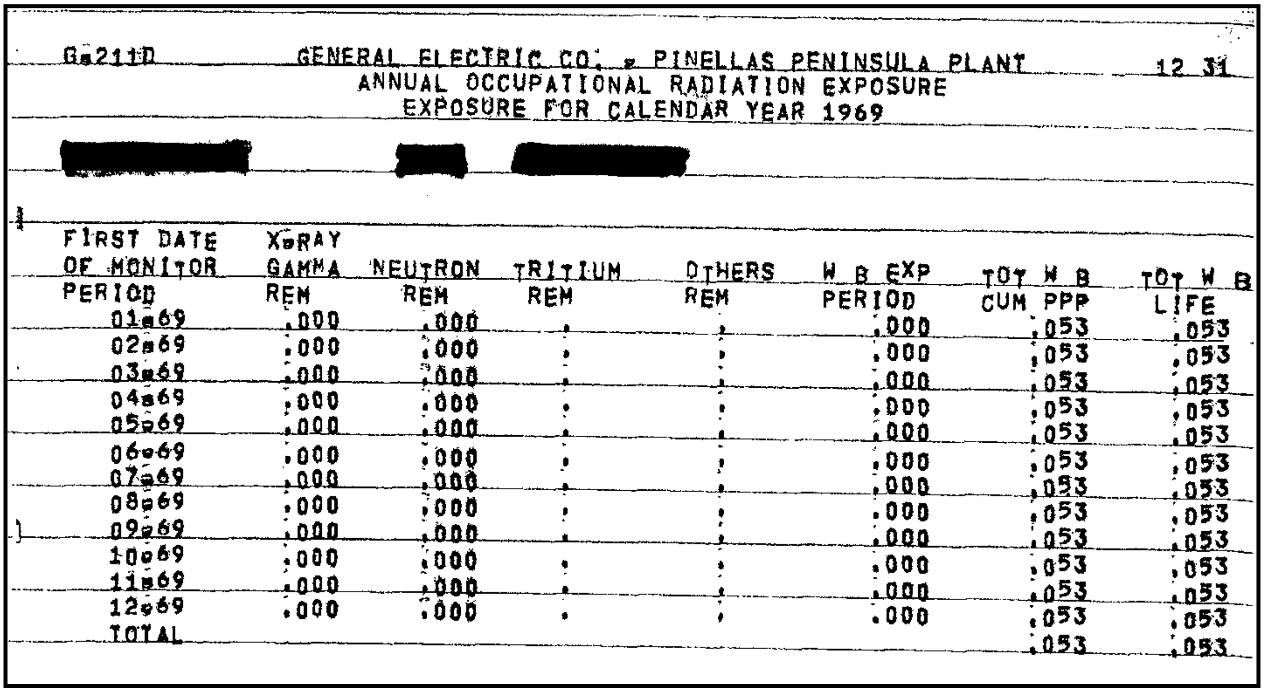
Name [redacted]
No. [redacted]
MUL-334-R-1

Date	uc/l	mrem(B)	mr(F)	mrem(F)	Total	Date	uc/l	mrem(B)	mr(F)	mrem(F)	Total
1-3	0.10	<20			<20	DEC.			<5	17	17
2-2	0.04	<20			<20				<	17	17
		<			<						
3-2	0.20	<20			<20						
		<			<						
4-6	0.01	<20			<20						
		<			<						
5-4	0.04	<20			<20						
		<			<						
6-1	0.00	<20			<20						
		<			<						
7-7	<	<20			<20						
		<			<						
6-61			<5	<17	<22						
JUL			<5	<8	<13						
			<	<	<						
AUG.			<5	<8	<13						
			<	<	<						
SEPT.			<5	<14	<19						
			<	<	<						
OCT.			<5	<14	<19						
			<	<	<						
NOV.			<5	<8	<13						
			<	<	<						

.C

ATTACHMENT A
EXAMPLES OF PINELLAS PLANT EXPOSURE RECORDS

Page 2 of 5



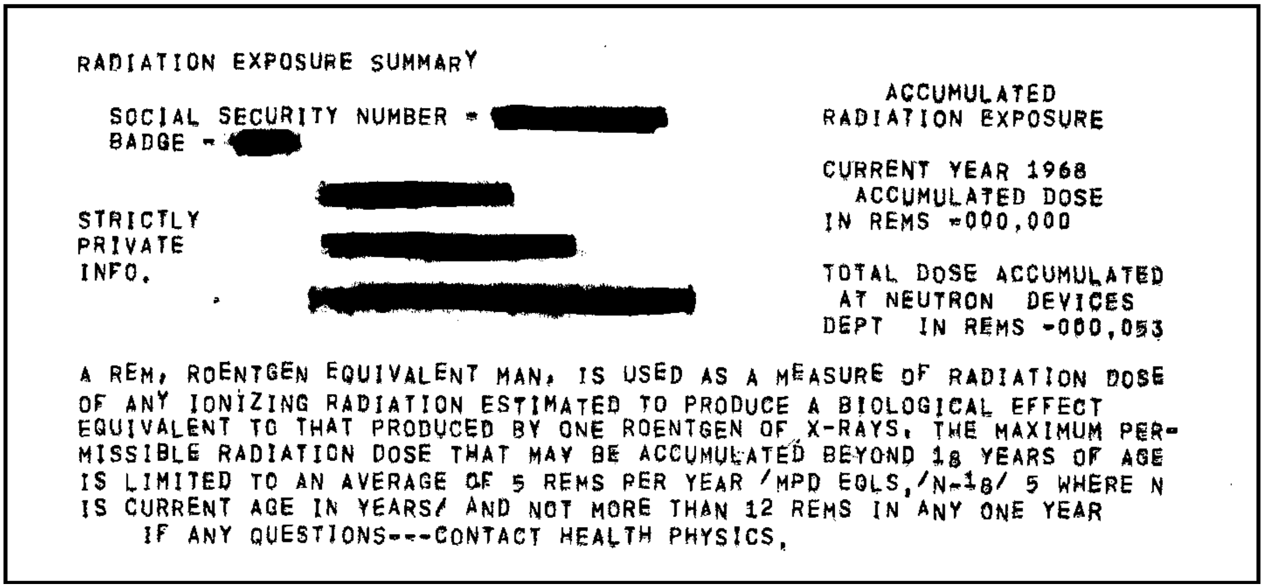
G-211D GENERAL ELECTRIC CO. - PINELLAS PENINSULA PLANT 12 31

ANNUAL OCCUPATIONAL RADIATION EXPOSURE

EXPOSURE FOR CALENDAR YEAR 1969

[redacted] [redacted] [redacted]

FIRST DATE OF MONITOR PERIOD	X-RAY GAMMA REM	NEUTRON REM	TRITIUM REM	OTHERS REM	W B EXP PERIOD	TOT W B CUM PPP	TOT W B LIFE
01-69	.000	.000	.	.	.000	.053	.053
02-69	.000	.000	.	.	.000	.053	.053
03-69	.000	.000	.	.	.000	.053	.053
04-69	.000	.000	.	.	.000	.053	.053
05-69	.000	.000	.	.	.000	.053	.053
06-69	.000	.000	.	.	.000	.053	.053
07-69	.000	.000	.	.	.000	.053	.053
08-69	.000	.000	.	.	.000	.053	.053
09-69	.000	.000	.	.	.000	.053	.053
10-69	.000	.000	.	.	.000	.053	.053
11-69	.000	.000	.	.	.000	.053	.053
12-69	.000	.000	.	.	.000	.053	.053
TOTAL						.053	.053



RADIATION EXPOSURE SUMMARY

SOCIAL SECURITY NUMBER - [redacted]
BADGE - [redacted]

[redacted]

STRICTLY
PRIVATE
INFO.

[redacted]

[redacted]

ACCUMULATED
RADIATION EXPOSURE

CURRENT YEAR 1968
ACCUMULATED DOSE
IN REMS -000,000

TOTAL DOSE ACCUMULATED
AT NEUTRON DEVICES
DEPT IN REMS -000,053

A REM, ROENTGEN EQUIVALENT MAN, IS USED AS A MEASURE OF RADIATION DOSE OF ANY IONIZING RADIATION ESTIMATED TO PRODUCE A BIOLOGICAL EFFECT EQUIVALENT TO THAT PRODUCED BY ONE ROENTGEN OF X-RAYS. THE MAXIMUM PERMISSIBLE RADIATION DOSE THAT MAY BE ACCUMULATED BEYOND 18 YEARS OF AGE IS LIMITED TO AN AVERAGE OF 5 REMS PER YEAR /MPD EQLS./N-18/ 5 WHERE N IS CURRENT AGE IN YEARS/ AND NOT MORE THAN 12 REMS IN ANY ONE YEAR

IF ANY QUESTIONS---CONTACT HEALTH PHYSICS.

ATTACHMENT A
EXAMPLES OF PINELLAS PLANT EXPOSURE RECORDS

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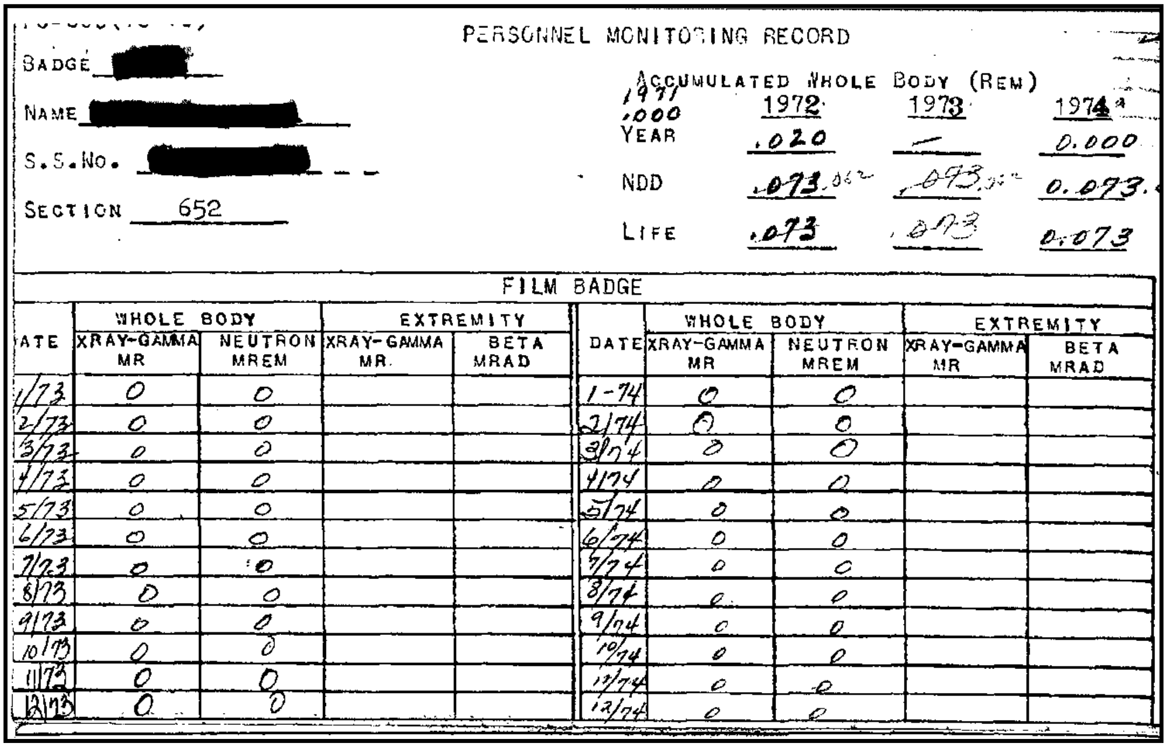


PERSONNEL MONITORING RECORD

BADGE [redacted]

NAME [redacted]

S.S.No. [redacted]

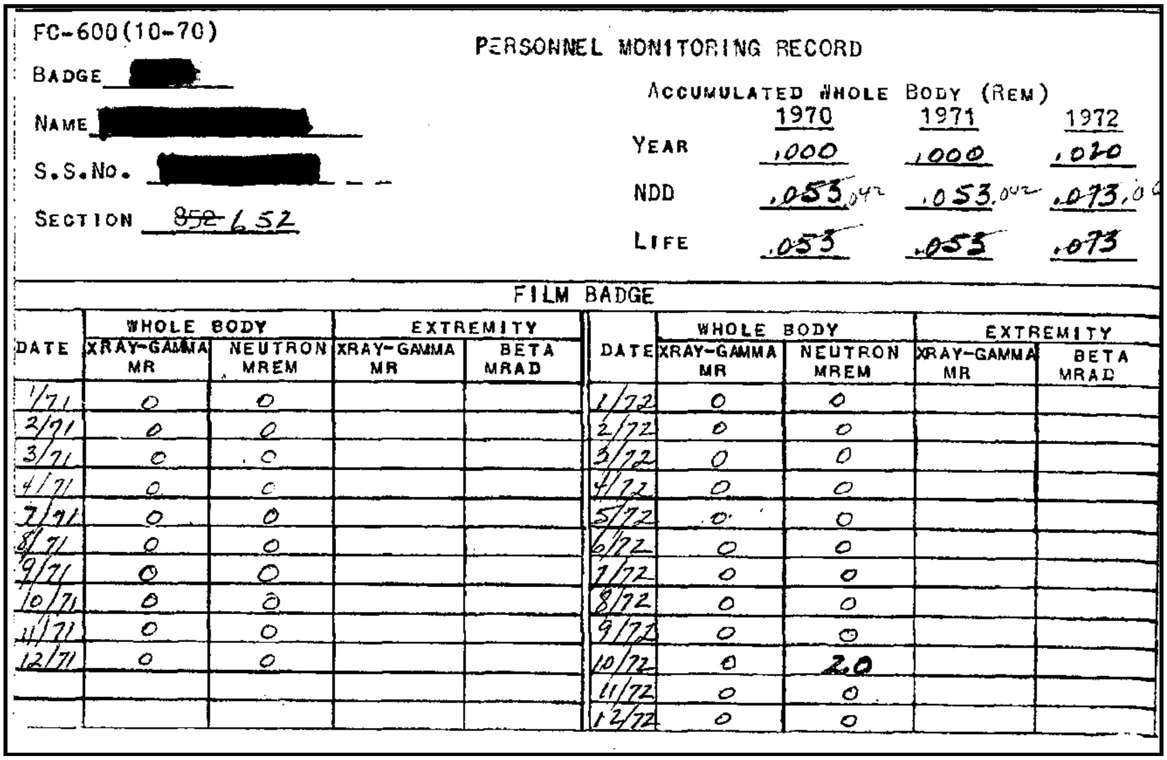
SECTION 652

ACCUMULATED WHOLE BODY (REM)

	1971	1972	1973	1974
YEAR	.000	.020	–	0.000
NDD		.073.062	.073.062	0.073.
LIFE		.073	.073	0.073

FILM BADGE

	WHOLE BODY		EXTREMITY			WHOLE BODY		EXTREMITY	
ATE	XRAY-GAMMA MR	NEUTRON MREM	XRAY-GAMMA MR.	BETA MRAD	DATE	XRAY-GAMMA MR	NEUTRON MREM	XRAY-GAMMA MR	BETA MRAD
1/73	0	0			1-74	0	0		
2/73	0	0			2/74	0	0		
3/73	0	0			3/74	0	0		
4/73	0	0			4/74	0	0		
5/73	0	0			5/74	0	0		
6/73	0	0			6/74	0	0		
7/73	0	0			7/74	0	0		
8/73	0	0			8/74	0	0		
9/73	0	0			9/74	0	0		
10/73	0	0			10/74	0	0		
11/73	0	0			11/74	0	0		
12/73	0	0			12/74	0	0		



FC-600(10-70)

PERSONNEL MONITORING RECORD

BADGE [redacted]

NAME [redacted]

S.S.No. [redacted]

SECTION ~~852~~ 652

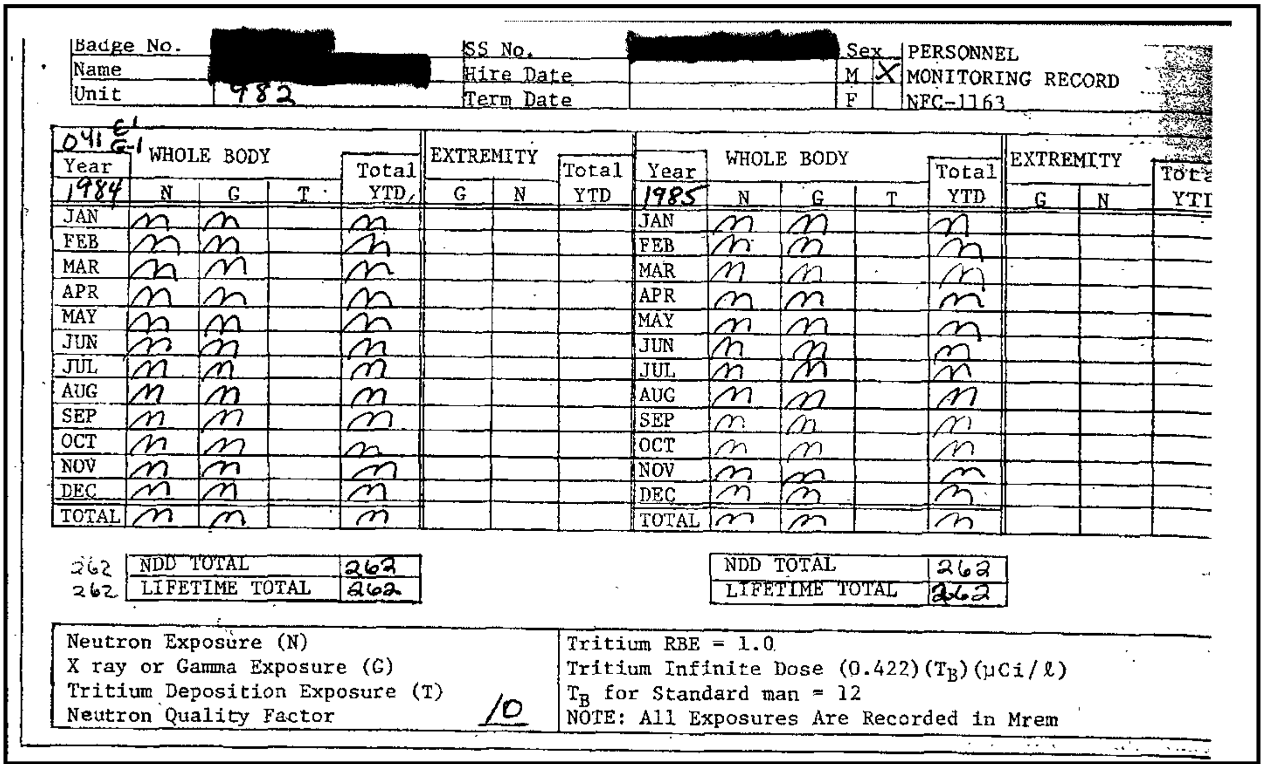
ACCUMULATED WHOLE BODY (REM)

	1970	1971	1972
YEAR	.000	.000	.020
NDD	.053.042	.053.042	.073.0
LIFE	.053	.053	.073

FILM BADGE

	WHOLE BODY		EXTREMITY			WHOLE BODY		EXTREMITY	
DATE	XRAY-GAMMA MR	NEUTRON MREM	XRAY-GAMMA MR	BETA MRAD	DATE	XRAY-GAMMA MR	NEUTRON MREM	XRAY-GAMMA MR	BETA MRAD
1/71	0	0			1/72	0	0		
2/71	0	0			2/72	0	0		
3/71	0	0			3/72	0	0		
4/71	0	0			4/72	0	0		
7/71	0	0			5/72	0	0		
8/71	0	0			6/72	0	0		
9/71	0	0			7/72	0	0		
10/71	0	0			8/72	0	0		
11/71	0	0			9/72	0	0		
12/71	0	0			10/72	0	20		
					11/72	0	0		
					12/72	0	0		

ATTACHMENT A
EXAMPLES OF PINELLAS PLANT EXPOSURE RECORDS
Page 4 of 5



Badge No.	[redacted]	SS No.	[redacted]	Sex	PERSONNEL MONITORING RECORD
Name	[redacted]	Hire Date		M ☒	
Unit	982	Term Date		F ☐	NFC-1163

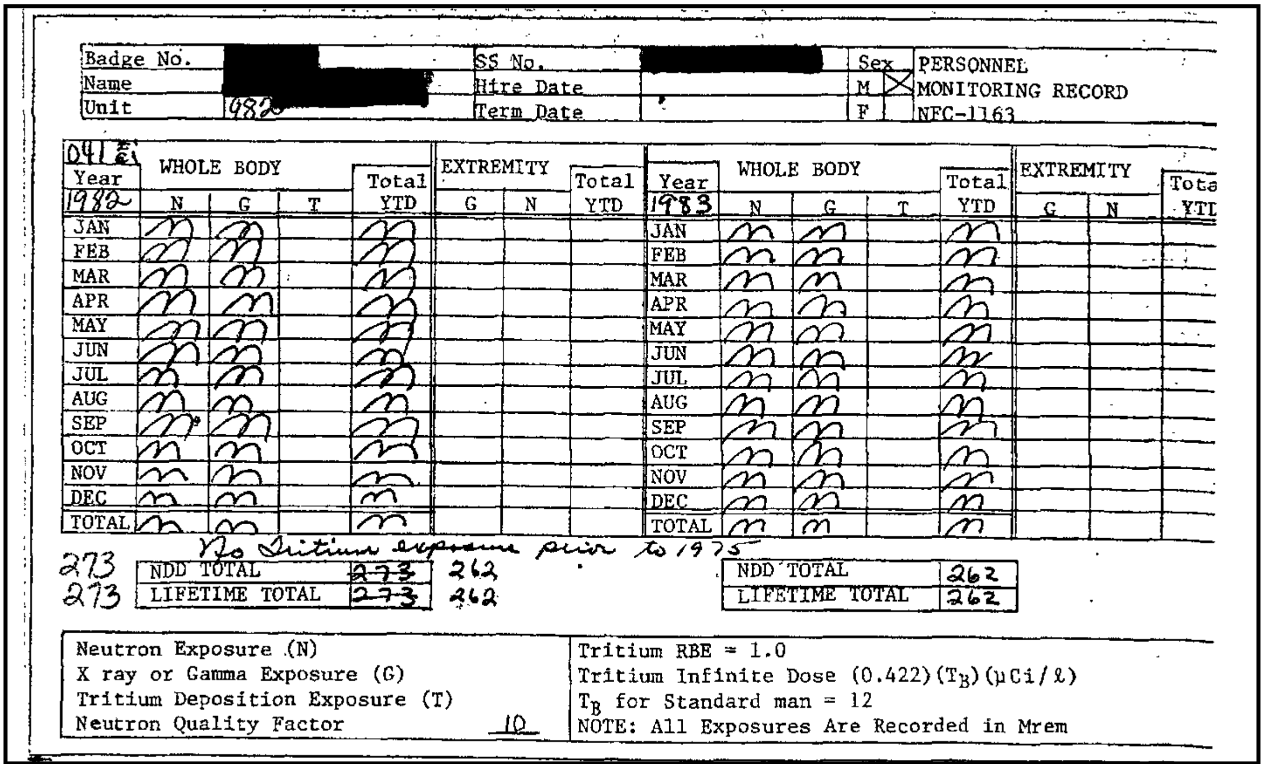
041 G-1 Year 1984	WHOLE BODY			Total YTD	EXTREMITY		Total YTD	Year 1985	WHOLE BODY			Total YTD	EXTREMITY		Tota YTI
	N	G	T		G	N			N	G	T		G	N	
JAN	m	m		m				JAN	m	m		m			
FEB	m	m		m				FEB	m	m		m			
MAR	m	m		m				MAR	m	m		m			
APR	m	m		m				APR	m	m		m			
MAY	m	m		m				MAY	m	m		m			
JUN	m	m		m				JUN	m	m		m			
JUL	m	m		m				JUL	m	m		m			
AUG	m	m		m				AUG	m	m		m			
SEP	m	m		m				SEP	m	m		m			
OCT	m	m		m				OCT	m	m		m			
NOV	m	m		m				NOV	m	m		m			
DEC	m	m		m				DEC	m	m		m			
TOTAL	m	m		m				TOTAL	m	m		m			

262 NDD TOTAL 262
262 LIFETIME TOTAL 262

NDD TOTAL 262
LIFETIME TOTAL 262

Neutron Exposure (N)
X ray or Gamma Exposure (G)
Tritium Deposition Exposure (T)
Neutron Quality Factor 10

Tritium RBE = 1.0
Tritium Infinite Dose (0.422)(T_B)(μCi/ℓ)
T_B for Standard man = 12
NOTE: All Exposures Are Recorded in Mrem



Badge No.	[redacted]	SS No.	[redacted]	Sex	PERSONNEL MONITORING RECORD
Name	[redacted]	Hire Date		M ☒	
Unit	982	Term Date		F ☐	NFC-1163

041 Year 1982	WHOLE BODY			Total YTD	EXTREMITY		Total YTD	Year 1983	WHOLE BODY			Total YTD	EXTREMITY		Tota YTI
	N	G	T		G	N			N	G	T		G	N	
JAN	m	m		m				JAN	m	m		m			
FEB	m	m		m				FEB	m	m		m			
MAR	m	m		m				MAR	m	m		m			
APR	m	m		m				APR	m	m		m			
MAY	m	m		m				MAY	m	m		m			
JUN	m	m		m				JUN	m	m		m			
JUL	m	m		m				JUL	m	m		m			
AUG	m	m		m				AUG	m	m		m			
SEP	m	m		m				SEP	m	m		m			
OCT	m	m		m				OCT	m	m		m			
NOV	m	m		m				NOV	m	m		m			
DEC	m	m		m				DEC	m	m		m			
TOTAL	m	m		m				TOTAL	m	m		m			

No Tritium exposure prior to 1975

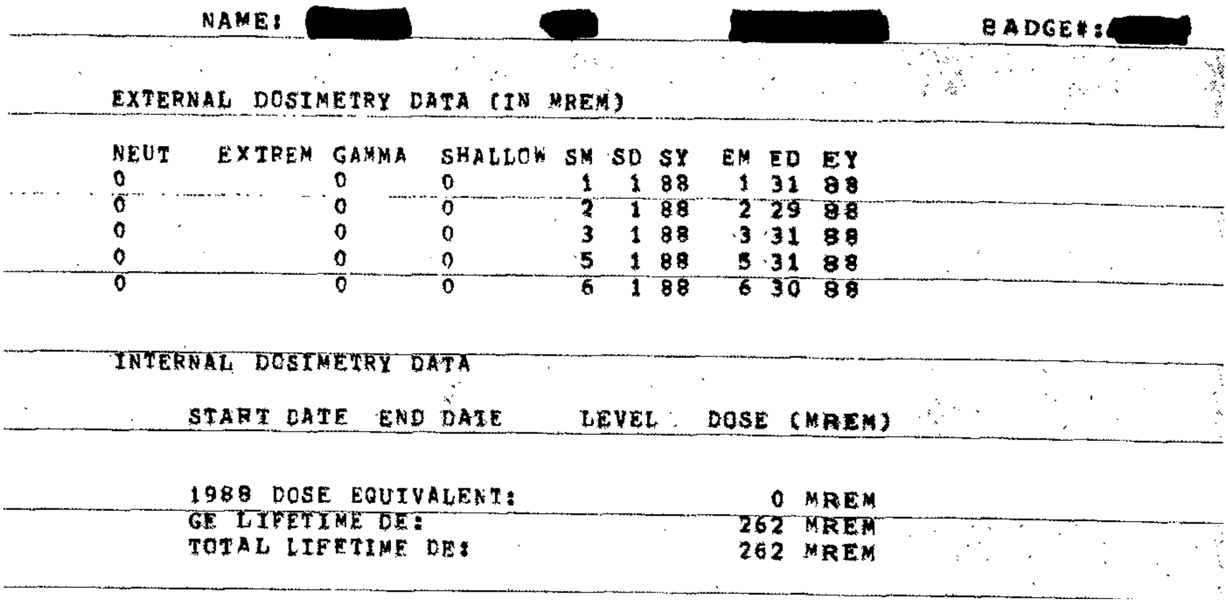
273 NDD TOTAL ~~273~~ 262
273 LIFETIME TOTAL ~~273~~ 262

NDD TOTAL 262
LIFETIME TOTAL 262

Neutron Exposure (N)
X ray or Gamma Exposure (G)
Tritium Deposition Exposure (T)
Neutron Quality Factor 10

Tritium RBE = 1.0
Tritium Infinite Dose (0.422)(T_B)(μCi/ℓ)
T_B for Standard man = 12
NOTE: All Exposures Are Recorded in Mrem

ATTACHMENT A
EXAMPLES OF PINELLAS PLANT EXPOSURE RECORDS
Page 5 of 5



```
          NAME: [redacted]     [redacted]     [redacted]          BADGE#:[redacted]

     EXTERNAL DOSIMETRY DATA (IN MREM)

     NEUT   EXTREM GAMMA  SHALLOW SM SD SY  EM ED EY
     0             0      0        1  1 88   1 31 88
     0             0      0        2  1 88   2 29 88
     0             0      0        3  1 88   3 31 88
     0             0      0        5  1 88   5 31 88
     0             0      0        6  1 88   6 30 88

     INTERNAL DOSIMETRY DATA

          START DATE  END DATE     LEVEL   DOSE (MREM)

          1988 DOSE EQUIVALENT:                 0 MREM
          GE LIFETIME DE:                     262 MREM
          TOTAL LIFETIME DE:                  262 MREM
```

ATTACHMENT B
BASIS FOR THE UNMONITORED EXTERNAL DOSE ASSIGNMENT

Background

Based on an evaluation of the available dosimetry records for the Pinellas Plant, personnel who had any potential to receive significant external dose were likely monitored. In addition, the majority of the work performed at the Pinellas Plant was nonradiological, which explains why a significant number of the employees were not monitored. However, there was the potential to receive incidental external doses that were small (i.e., < 20 mrem/yr) but were much more significant than the highest onsite ambient doses for the plant [i.e., >> 3.66×10^{-13} mrem/yr, from the Plant's environmental dose TBD (ORAUT 2011c)]. One of the most common types of incidental radiation exposures was attributable to Plant tours, which included visits to the neutron generator testing areas. Based on information provided in the telephone interviews, personnel on these tours were allowed to witness the neutron generators being tested without being provided with dosimetry. Based on information that has been provided in some Pinellas Plant records, doses at the 3-ft exclusion boundary for the neutron generator tests were 9.9 mrem per test. Assuming that personnel on a Plant tour would not have likely stayed in the neutron generator testing area for more than two tests, these exposed personnel might have received an incidental dose of almost 20 mrem.

Because the incidental doses at the Pinellas Plant were likely much larger than the onsite ambient doses, it is not appropriate to assign onsite ambient doses to all unmonitored workers unless it can be established that there was no potential for incidental dose due to an employee's job. Because a determination that incidental doses were not received can rarely be defended, unmonitored external doses should be assigned for all workers in lieu of the onsite ambient doses for the Plant.

Basis for Upper-95th Percentile Dose of 100 mrem/yr for Unmonitored Workers

A review of the available dosimetry data for the Pinellas Plant indicates that on average 95% of the monitored workers at the plant received annual doses ≤ 100 mrem. This determination is based on an evaluation of whole-body dose information that was available in the following documents: GE 1956–1980, 1957–1990, 1975; Greene 1985b, 1986; Holliday 1977, 1979, 1981, 1983b; Jech 1963; LMSC 1996; Schumacher 1982, 1983, 1984; and Weaver 1994b.

Whole-body dose information was used for the evaluation because it was the only form of data that was consistently available throughout the years the Pinellas Plant operated. Unfortunately, the Plant's reported whole-body doses consist of external photon, external neutron, and internal tritium doses, and the contribution attributable to each of these components cannot be determined for most years. In addition, the doses evaluated represent population doses that do not account for potential missed doses. Table B-1 provides summarized results of the dosimetry data that were evaluated. The average percentage of annual whole-body doses below 100 mrem was 94.7% (95% when rounded to the nearest percent), for the years that were evaluated. However, for a select number of years, more detailed dose information was provided, and it was determined that a significant number of the annual whole-body doses were either entirely or mostly attributable to tritium dose. This is consistent with the types of operations performed at the Pinellas Plant. Therefore, the upper-95th-percentile external dose for monitored workers is likely to be less than 100 mrem/yr.

ATTACHMENT B
BASIS FOR THE UNMONITORED EXTERNAL DOSE ASSIGNMENT

Table B-1. Evaluation of Pinellas Plant doses available in the SRDB.

Year	Total number of annual doses checked	Number of annual doses ≥ 100 mrem	Percentage of annual doses below 100 mrem	Number of annual doses ≤ 20 mrem	Percentage of annual doses ≤ 20 mrem
1957	71	12	83.1	38	53.5
1958	142	4	97.2	102	71.8
1959	205	43	79.0	114	55.6
1960	232	40	82.8	147	63.4
1961	265	39	85.3	168	63.4
1962	259	36	86.1	159	61.4
1963	258	20	92.2	197	76.4
1964	292	13	95.5	212	72.6
1965	280	37	86.8	233	83.2
1966	320	17	94.7	277	86.6
1967	351	8	97.7	328	93.4
1968	355	3	99.2	340	95.8
1969	344	9	97.4	326	94.8
1970	293	9	96.9	258	88.1
1971	282	6	97.9	261	92.6
1972	292	7	97.6	267	91.4
1973	280	10	96.4	254	90.7
1974	303	8	97.4	265	87.5
1975	276	2	99.3	246	89.1
1976	255	5	98.0	195	76.5
1977	246	27	89.0	159	64.6
1978	262	20	92.4	176	67.2
1979	313	17	94.6	244	78.0
1980	383	23	94.0	249	65.0
1981	388	18	95.4	324	83.5
1982	418	4	99.0	286	68.4
1983	396	11	97.2	263	66.4
1984	428	13	97.0	296	69.2
1985	395	15	96.2	253	64.1
1986	322	NA[a]	NA[a]	NA[a]	NA[a]
1987	248	NA[a]	NA[a]	NA[a]	NA[a]
1988	263	4	98.5	245	93.2
1989	285	5	98.2	270	94.7
1990	284	4	98.6	258	90.8
1991	288	1	99.7	274	95.1
1992	280	0	100.0	275	98.2
1993	245	0	100.0	242	98.8
1994	NA	NA[a]	NA[a]	NA[a]	NA[a]
1995	215	0	100.0	NA[a]	NA[a]
1996	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]
1997	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]
1998	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]
Averages			94.7		79.6

a. NA – not available.

Upon review of the dosimetry data in the referenced documents listed above and Table 6-1 of this document, many discrepancies regarding the numbers of individuals monitored were noted. Therefore, it is not recommended that the 95th-percentile doses for individual years be tabulated unless a better data set is located. By averaging the data over several years, the potential for incurring a significant error for a given year would be minimized. In addition, including the dose contribution attributable to tritium helps to compensate for any potential errors and helps to ensure that the 95th-percentile dose is favorable to claimants. Because the majority (>79% each year on average) of the annual whole-body doses reported for Pinellas Plant workers were ≤ 20 mrem, which is an individual dosimeter's limit of detection for some of the dosimeters used at the Plant, it appears that the Plant monitored workers if they had any potential to receive dose. As a result, it is unlikely that any unmonitored workers would have received doses approaching the upper-95th-percentile doses. Therefore, it is very unlikely that any errors in the 95th-percentile dose calculation attributable to these discrepancies would result in an unfavorable to claimant dose assignment for unmonitored individuals.

Comparison of Maximum Likelihood Doses for Unmonitored Workers to the Unmonitored Dose Assignment

Area dosimeter results with their placement locations identified in relation to the external radiation source terms are very limited. However, detailed area dosimeter results were available for the period from 1984 through June 1986 in GE (1984–1986).

The area dosimeter results available for Areas 128, 131, and 183 were evaluated. These areas represent photon and neutron exposure areas, which are in the neutron generator operational areas of the Plant. Area 131 was the final testing area of the neutron generators. Area 128 was represented by dosimeter locations 9000, 9001, 9003, 9004, 9008, and 9019. Area 131 was represented by dosimeter locations 9026 and 9038. Area 183 was represented by dosimeter location 9020. All of these dosimeter locations were reported as being within 24 to 65 in. of the closest radiation source. For the period from 1984 through June 1986, only a single photon dosimeter result above the dosimeter's LOD was reported and only two neutron dosimeter results at two different locations were reported as being above the dosimeter's LOD.

Based on the area dosimeter data that were evaluated, the worst-case annual photon dose is 20 mrem plus 11 dosimeters worth of missed dose, and the worst-case annual neutron dose is 40 mrem plus 11 dosimeters worth of missed dose. Because area dosimeter results correspond to a 8,760-hour year versus a 2,500-hour work-year, the worst-case annual doses needed to be adjusted by a maximized occupancy factor of 0.2854 (2,500/8,760). For the photon and neutron dosimeters used during this period, no other dose adjustments were needed as indicated in Section 6.3. For 1984–1986, the LOD/2 values for the applicable photon and neutron dosimeters were 5 mrem and 10 mrem per dosimeter exchange, respectively. Based on those values, the maximum likely external dose to an unmonitored worker would be <64 mrem/yr (21 mrem/yr from photons and 43 mrem/yr from neutrons). Because it is unlikely that a Pinellas Plant worker would have spent 100% of their time within 65 in. of a radiation source without being monitored, this is likely a significant overestimate of an unmonitored worker's potential external dose.

The potential doses to workers in the RTG areas of Building 400 are potentially much higher than 64 mrem/yr. However, because all types of plutonium are considered to be special nuclear material, access to the RTG areas was more strictly limited. Because Pinellas Plant personnel having work assignments in radiation areas were required to wear dosimeters per General Operating Procedures (Greene 1985b; GE 1982), and because access to the RTG areas would have been controlled for security purposes, it is much less likely that personnel would have been able to receive significant unmonitored doses in the RTG areas. Therefore, the potential doses for unmonitored workers in the RTG areas were also likely less than 64 mrem/yr.

Not Using ORAUT-OTIB-0020 Approach for Calculating Coworker Doses
Because an unmonitored worker's potential to receive external dose at the Pinellas Plant was significantly less than the dosimetry program's ability to detect doses that low, the unmonitored dose approach described in ORAUT-OTIB-0020 (ORAUT 2008), which uses only coworker data, can result in an unreasonable overestimate of an unmonitored Pinellas Plant worker's external doses. This determination is supported by an analysis of the available area dosimeter results, which have a longer effective monitoring period per dosimeter exchange, and the fact that on average >79% of the annual whole-body doses reported for Plant workers were ≤ 20 mrem.

The ORAUT-OTIB-0020 approach requires a favorable-to-claimant LOD/2 approach for accounting for the coworker's potential missed doses (ORAUT 2008). Based on the maximum likelihood doses calculated above, the ORAUT-OTIB-0020 approach results in an unreasonably excessive unmonitored dose estimate for unmonitored Pinellas Plant workers. Because of this and because the 95th-percentile dose is already greater than the maximum likelihood dose, the potential missed doses were not factored into the unmonitored dose assignment for the Pinellas Plant. Another alternative would be to use the maximum likelihood dose of 64 mrem/yr as the unmonitored dose assignment. However, a decision was made to use the more favorable-to-claimant unmonitored dose assignment of 100 mrem/yr to ensure that the worker's external doses are not underestimated.

Assigning Unmonitored Doses as Photon Doses Versus Neutron Doses
Because the unmonitored external dose assignment includes both photon and neutron dose components and because the proportions of those dose components are unknown and highly variable, an evaluation was performed to determine which of the applicable radiation types and energy groups to assign the unmonitored doses as.

The only photon energy distribution that is used for the external doses for Pinellas Plant workers is 100% 30-250 keV photons, which is also the most favorable-to-claimant photon energy distribution. Therefore, only 30-250 keV photons were evaluated for the potential unmonitored dose assignment.

Based on the information in the main body of this document, there are only two neutron energy distributions for the various areas at the Pinellas Plant. For the neutron generators areas at the Plant, the neutron energy distribution was 100% 2-20 MeV neutrons. For the RTG areas in Building 400, the neutron energy distribution was 50% 0.1-2 MeV and 50% 2-20 MeV neutrons. Given that it was unlikely that a worker would have been able to spend any significant time in the presence of the PuO_2 sources in the RTG areas without having to wear a dosimeter, the predominant neutron energies that unmonitored workers at the Plant were likely exposed to were 2-20 MeV neutrons. Therefore, only 2-20 MeV neutrons were evaluated for the potential unmonitored dose assignment.

The unmonitored dose assignment of 100 mrem/yr was assigned as photon dose and then neutron dose to compare the POC results using each of the IREP cancer models. Because ORAUT-OTIB-0005 (ORAUT 2011a) indicates that there could be multiple external organ dose selections for a given IREP cancer model, this evaluation was performed using only the external organ dose selection that resulted in the highest dose (i.e., the selection with the highest organ DCF) for a given IREP cancer model selection. Each IREP cancer model was evaluated using the following hypothetical scenario assumptions:

ATTACHMENT B
BASIS FOR THE UNMONITORED EXTERNAL DOSE ASSIGNMENT

1. The hypothetical worker was a male, with the exception of cancer models that are only applicable to females.

2. The worker was 18 years old at the time of the first exposure. Therefore, a year of birth of 1939 and a first year of employment date of 1957 were selected.

3. The worker was assumed to be employed and unmonitored for 5 years (i.e., during all of 1957 through 1961).

4. Only an unmonitored dose of 100 mrem was assigned for each year of employment.

5. The date of diagnosis was set at 12 years after the last year of employment (i.e., 1973).

Because the unmonitored dose assignment represents a population dose, no uncertainty correction factors were applied to the unmonitored dose assignment. As indicated in the main body of this document, no dosimeter correction factors need to be applied to the photon doses. Even though the main body of this document indicates that dosimeter corrections factors would be applied to the reported neutron doses for most years, no dosimeter correction factors were applied when the unmonitored doses were evaluated as neutron doses. The basis for this is that the unmonitored dose assignment is essentially an arbitrary value that has been determined to be more favorable to claimants than the maximum likelihood dose for the Pinellas Plant, and the evaluation of the maximum likelihood dose for the Plant utilized neutron dosimeter data that did not require any adjustments, as indicated in Section 6.3. In addition, the ICRP Publication 60 correction factor for 2-20 MeV neutron doses is 1.00 for the Plant, so this correction factor had no impact on the neutron doses being evaluated (ICRP 1991).

The results of this evaluation are summarized in Table B-2 below. With the only exceptions being the acute myeloid leukemia, chronic myeloid leukemia, and leukemia (less chronic lymphocytic leukemia) IREP cancer models, the assignment of the unmonitored doses as 100% 30-250 keV photons provides a more favorable-to-claimant POC. At the time of this document’s preparation, it was determined that out of 393 Pinellas Plant claims, which excludes pulled claims, there are only 5 leukemia claims that are affected by the photon-versus-neutron unmonitored dose issue. However, because the unmonitored workers at any site only need to be assigned 50th-percentile coworker doses and because the unmonitored external dose assignment is greater than the maximum likelihood dose, assigning an unmonitored external dose of 100 mrem/yr as only photon dose is still considered to be favorable to claimants for the leukemia cases based on the results of this evaluation.

ATTACHMENT B
BASIS FOR THE UNMONITORED EXTERNAL DOSE ASSIGNMENT

Table B-2. Evaluation of POCs associated with assigning unmonitored doses as either photon or neutron dose.

Applicable cancer models	Worst-case external dose organ selection	Photon dose POC (%)	Neutron dose POC (%)
Acute lymphocytic leukemia	Red bone marrow	17.89	11.01
Acute myeloid leukemia	Red bone marrow	10.59	11.83
All digestive	Stomach	4.34	2.56
All male genitalia	Testes	3.57	2.21
Bladder	Bladder	4.68	3.52
Bone	Bone surfaces	4.98	3.38
Breast	Breast (female)	7.58	4.04
Chronic myeloid leukemia	Red bone marrow	12.63	12.71
Colon	Colon	5.33	3.96
Connective tissue	Thyroid	5.36	3.45
Esophagus	Esophagus	4.95	3.99
Eye	Eye	4.72	3.08
Female genitalia (less ovary)	Bladder	0.04	0.03
Gallbladder	Bladder	11.66	6.65
Leukemia (less CLL)	Red bone marrow	15.69	18.34
Liver	Liver	17.14	10.61
Lung	Thyroid	5.72	3.03
Lymphoma and multiple myeloma	Thyroid	3.43	1.77
Malignant melanoma	Skin	10.09	7.63
Nervous system	Thyroid	2.41	1.45
Non-melanoma (BCC)	Skin	10.20	7.82
Non-melanoma (SCC)	Thyroid	0.33	0.15
Oral cavity and pharynx	Thyroid	2.59	1.54
Other and ill-defined sites	Thyroid	5.19	3.13
Other endocrine	Thyroid	6.30	4.00
Other respiratory	Thyroid	2.26	1.05
Ovary	Bladder	5.42	3.84
Pancreas	Stomach	2.47	1.60
Rectum	Colon	1.70	1.17
Stomach	Stomach	7.95	4.81
Thyroid	Thyroid	16.08	7.10
Urinary organs (less bladder)	Testes	6.24	4.24