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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Thermoluminescent Dosimeter Use for Environmental Surveillance at the Hanford Site, 1971–2005

EJ Antonio
TM Poston
BA Rathbone

March 2010

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The U.S. Department of Energy (DOE) requires that environmental monitoring programs be conducted at its Hanford Site in south-central Washington to protect the site's environmental and cultural resources, the public, and site workers by achieving site and contractor compliance with environmental, public health, and resource protection laws, regulations, and DOE Orders. Pacific Northwest National Laboratory (PNNL) manages Public Safety and Resource Protection Projects (PSRPP) for DOE's Richland Operations Office to monitor the Hanford environment, provide assurance that the site is operated in compliance with applicable environmental regulations, and conduct impact assessments to protect public and worker safety and Hanford's ecological and cultural resources. Under the PSRPP, the Surface Environmental Surveillance Project is responsible for measuring the concentrations of radiological and nonradiological contaminants in environmental media and for assessing the potential impacts of these materials on the environment and the public. Various media are collected onsite in the 600 Area, and offsite at perimeter, community, and distant locations. Samples of air, surface water and sediment, farm products, wildlife, and vegetation are routinely collected and analyzed for radionuclides and various chemical constituents. From 1971 through 2005, ambient external radiation was also measured at selected locations on and off the site.

This report briefly describes the principles of thermoluminescent dosimetry and the various thermoluminescent dosimeter (TLD) systems that have been used at Hanford for environmental surveillance of external radiation over its operational history largely by PNNL under the so-called Hanford Environmental Surveillance TLD Program, or simply the TLD program. It presents the results of a review of the measurement of external radiation using TLDs outside of industrialized areas on the site, at locations along the river shoreline, and in areas adjacent to and distant from the Hanford Site. Quality assurance practices and independent measures of system performance are discussed, supplemented by summaries of TLD results from January 1971 through December 2005 (when the TLD program was terminated) and analysis of observed trends. Summary figures and narrative discussion of TLD readings at each surveillance location are included for both terrestrial (onsite and offsite) locations and riparian (Columbia River shoreline) locations.

An apparent increase in environmental exposure rates was observed from 1985 through 1989 after a large-scale exchange of TLD chips. Part of the increase is believed to be attributable to the greater sensitivity of replacement TLD chips to low-energy photons, and possible changes in calibration practices in the TLD processing laboratory. Analysis of variance showed that there was a significant difference in TLD readings based on dosimeter type and that, historically, there was a significant difference in readings between location groupings of TLDs (i.e., onsite, perimeter, community, or distant groupings). Overall, dose rates observed at surveillance locations generally reflected background exposure rates with increases observed at the locations closest to known sources of radioactive materials. As the site has transitioned from plutonium production to waste management, cleanup, and restoration, external radiation levels have decreased to background levels at most surveillance sampling locations.

Acknowledgments

The authors express their appreciation to K Rhoads for critical reviews of this report. LE Bisping provided the data from the Hanford Environmental Information System database. Thermoluminescent dosimeters were deployed over the 35-year period covered by this report by numerous radiation control technicians under the supervision of MR Quarders, EW Lusty, SF Conley, and RW Hanf, Jr. Several PNNL scientists including JE Fix, KR Price, MJ Sula, RL Dirkes, and W James have provided guidance for external radiation surveillance. SK Ennor served as technical editor and KR Neiderhiser provided formatting and text processing support. We also thank the U.S. Department of Energy and its predecessor agencies (U.S. Atomic Energy Commission and the Energy Research and Development Administration) for their support.

Acronyms and Abbreviations

ABS	acrylonitrile butadiene styrene
ALE	Fitzner/Eberhardt Arid Lands Ecology Reserve
ANSI	American National Standards Institute
ANOVA	Analysis of Variance
°C	degree(s) Celsius
CaF_2:Dy	calcium fluoride:dysprosium
CaF_2:Mn	calcium fluoride:manganese
$CaSO_4$:Dy	calcium sulfate:dysprosium
cm	centimeter(s)
cm^2	square centimeter(s)
CY	calendar year
d	day(s)
DOE	U.S. Department of Energy
DOE-RL	DOE Richland Operations Office
eV	electron volt(s)
FFTF	Fast Flux Test Facility
GPS	global positioning system
h	hour(s)
HEIS	Hanford Environmental Information System
HTLTR	High Temperature Lattice Test Reactor
HTR	Hanford Test Reactor
keV	thousand electron volt(s)
LiF:Mg,Ti	lithium fluoride:manganese, titanium
LIGO	Laser Interferometer Gravitational Wave Observatory
MeV	million electron volts
mg	milligram(s)
mGy	milligray(s)
mR	milliroentgen(s)
mrem	millirem(s)

nC	nanocoulomb(s)
NIST	National Institute of Science and Technology
P_i	performance quotient
PCTR	Physical Constants Test Reactor
PIC	pressurized ionization chamber
PMT	photomultiplier tube
PNNL	Pacific Northwest National Laboratory
PRCF	Plutonium Recycle Critical Facility
PRF	Plutonium Reclamation Facility
PRTR	Plutonium Recycle Test Reactor
PSRPP	Public Safety and Resource Protection Projects
PUREX	Plutonium-Uranium Extraction (facility)
QC	quality control
R&D	research and development
rad	radiation adsorbed dose
RECUPLEX	Recovery of Uranium and Plutonium by Extraction (facility)
REDOX	Reduction-Oxidation (Plant)
RMA	Remote Mechanical A Line
RMC	Remote Mechanical C Line
s	second(s)
SESP	Surface Environmental Surveillance Project
TLD	thermoluminescent dosimeter
TTR	Thermal Test Reactor
UO_3	uranium trioxide
µR	micro Roentgen(s)
yr	year
WDOH	Washington State Department of Health
WNP	Washington Nuclear Plant
WPPSS	Washington Public Power Supply System (now Energy Northwest)

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1.0 Introduction

U.S. Department of Energy (DOE) Orders 450.1, "Environmental Protection Program," and 5400.5, "Radiation Protection of the Public and the Environment," require that environmental monitoring programs be conducted at Hanford to verify the protection of the site's environmental and cultural resources, the public, and workers on the site. The monitoring activities support the site's integrated Safety Management System Policy (DOE 1996) and its component Environmental Management System. Component systems are tools for achieving site and contractor compliance with environmental, public health, and resource protection laws, regulations, and DOE Orders. The DOE Richland Operations Office's (DOE-RL's) Environmental Monitoring Plan (DOE 2007) is the mechanism through which monitoring programs and projects are implemented at Hanford.

Public Safety and Resource Protection Projects (PSRPP) are managed for the DOE-RL by Pacific Northwest National Laboratory (PNNL). The purpose of the projects is to monitor the Hanford environment, provide assurance that the site is operated in compliance with applicable environmental regulations, and conduct impact assessments to protect public and worker safety and Hanford's ecological and cultural resources. Projects under the PSRPP include the Meteorological and Climatological Services Project, the Cultural Resources Project, the Ecological Monitoring and Compliance Project, and the Surface Environmental Surveillance Project (SESP). The SESP is responsible for measuring the concentrations of radiological and nonradiological contaminants in environmental media onsite in the 600 Area and offsite at perimeter, community, and distant locations and assessing the potential impacts of these materials on the environment and the public. Samples of air, surface water and sediment, farm products, wildlife, and vegetation are routinely collected and analyzed for radionuclides and chemical content. From 1970 through 2005, ambient external radiation using thermoluminescent technology was also measured at selected locations on and off the site.

1.1 Environmental Surveillance at the Hanford Site

The Hanford Site presently encompasses 586 square miles of predominantly arid sagebrush and grasslands located in south-central Washington State. The site was initially established during World War II as part of the Manhattan Project to produce plutonium, and the production operations expanded considerably during the Cold War. Today, it is one of DOE's largest environmental cleanup sites in terms of physical size and budget. Environmental surveillance and monitoring to assess and document radiological conditions began at Hanford in 1944 when B Reactor first started operations and began to discharge cooling water to the Columbia River (Marceau 2003). With the advent of large-scale plutonium production and the associated waste management activities, site monitoring activities were expanded to address the uncertainties of the newly evolving nuclear technologies. Most site surveillance involved the measurement of radionuclide concentrations in environmental media including air, water, soil, biota, and farm products.

Environmental monitoring at Hanford branched into two operational programs. The operating contactors at the site performed what came to be known as the near-field monitoring program that focused on facilities and effluent streams from the Central Plateau waste management areas and the reactor areas along the Columbia River. Over the years covered in this report (January 1971–December 2005), the operating contractors were Atlantic Richfield Hanford Company, Rockwell Hanford Operations, Westinghouse Hanford Company, and Fluor Hanford, Inc. (Harvey 2003). Pacific Northwest Laboratory

was formed in 1965 as the site diversified, with Battelle Memorial Institute operating the research facilities for DOE. These research facilities at Hanford became the Pacific Northwest National Laboratory (PNNL) in 1995. PNNL assumed responsibility for activities designated as far-field monitoring, which included environmental sampling from facility fence lines to the Hanford Site boundary and beyond. The scope of monitoring conducted by PNNL has been referred to as environmental surveillance to distinguish it from the near-field monitoring conducted by Hanford Site operating contractors. PNNL also has responsibility for monitoring at the fence line in the 300 and 400 Areas of the Hanford Site.

One key element of environmental monitoring at Hanford Site was the direct measurement of external radiation. Initial monitoring of external radiation in the open environment used field survey instruments and pencil dosimeters (sometimes called pocket ionization chambers) (Corley 1973). The pencil dosimeters were initially developed for monitoring worker exposure to gamma radiation, and that technology was eventually replaced by development of thermoluminescent dosimeters (TLDs). This report summarizes the environmental surveillance of external radiation performed by PNNL from 1970 to 2005 and does not address near-field monitoring programs conducted by other site contractors. In this report, we designate PNNL's environmental surveillance of external radiation as the Hanford Environmental Surveillance TLD Program, or simply the TLD program.

Although various types of TLDs had been under development since the 1950s, the formal establishment of the Hanford Environmental Surveillance TLD Program did not occur until June 1970 at Hanford. Like the pencil dosimeters, the TLDs were initially developed to monitor the radiation exposure of workers (Frame 2004). During the 1960s and 1970s, measurements were made in the Columbia River using both TLDs and pocket dosimeters. These surveillance operations have been summarized annually in reports since 1959 and most of the reports are available electronically (http://sesp.pnl.gov/Reports/Reports.HTML). Routine surveillance of external gamma radiation, or "penetrating" radiation as it was identified in some site environmental reports, was conducted using TLDs from 1970 through 2005. The program was terminated in 2005 due to budgetary constraints and prioritization of other environmental surveillance objectives.

Other programs at Hanford used TLDs for environmental applications and personnel exposure monitoring, effluent monitoring, and field research. TLDs were used for research projects before they were used for routine environmental surveillance. Lithium-fluoride powder TLDs were used to estimate the external radiation exposure of periphyton (Lappenbusch et al. 1971) and other aquatic organisms in 1968 and 1969 (Watson and Templeton 1973). These measurements were taken downstream of the 100-K reactors and at other points both upstream and downstream of the reactor liquid effluent discharge structures. The same technology was used for studies at Hanford low-level radiological waste management ponds (Guthrie and Scott 1969; Emery and McShane 1978). TLD chips were also placed in mice to estimate in situ dose rates near low-level waste ponds (Gano 1979) and around the 300 Area burial grounds (Fitzner et al. 1979). Data from those research projects are not included in the scope of this report.

1.2 Purpose and Scope

Although there have been numerous summaries of surveillance activities at Hanford addressing the accumulation and trends of radionuclide concentrations in environmental media over the past 35 years

(e.g., Price and Kinnison 1982; Price 1988; Eberhardt et al. 1989; Patton and Cooper 1993; Antonio et al. 1993; Antonio 1994; Dirkes 1994; Poston 1994; Poston and Cooper 1994; Fritz and Patton 2002), there have been few long-term summaries of external radiation data. The initial 5 years of TLD deployment for surveillance purposes were summarized by Fix et al. (1977). Additional information about the measurement of external radiation along the Columbia River shoreline can be found in a report by Sula (1980). However, there has been no previous summary that covers the entire 35 years of environmental surveillance TLD measurements and methods used at Hanford. To fill this gap, the historical external environmental radiation data were reviewed, and this report was prepared to meet the following basic objectives:

1. Review the principles of thermoluminescent dosimetry and the design changes in TLDs deployed for environmental surveillance.
2. Review the measurement of external radiation with TLDs outside of industrialized areas on the site, at locations along the river shoreline, and in areas adjacent to and distant from the Hanford Site.
3. Evaluate the performance and quality control practices of the TLD program.

1.3 Report Contents and Organization

To meet the objectives of the review of TLD-based environmental surveillance practices, the following sections of this report first provide an overview of the Hanford Environmental Surveillance TLD Program (Section 2.0), an analysis of environmental TLD results from 1970 through 2005 (Section 3.0), and related discussion (Section 4.0). Supplemental information is provided in appendices. Appendix A contains TLD graphical data summaries by sample location for upland terrestrial locations on and off the Hanford Site. Appendix B contains similar data summaries by sample location for riparian (Columbia River shoreline) locations. Appendix C provides an overview of Hanford plutonium production operations and related facilities.

2.0 Hanford Environmental Surveillance TLD Program

An understanding of the Hanford Environmental Surveillance TLD Program and its significance requires an understanding of the objectives of the program, the principles behind the technology, and general program operations.

Initially, TLDs were deployed into the Hanford environment as a means of monitoring what collectively can be called external penetrating radiation levels. By design, TLDs measure gamma radiation; however, the more sensitive designs can detect energetic beta radiation if the TLD chip has not been purposely shielded. Natural sources of gamma radiation include radionuclides present in soil, water, and air as well as extraterrestrial cosmic radiation. TLD technology was applied to address several surveillance objectives (listed below) that are best described in the Hanford Site Environmental Management Plan (DOE 2007):

1. Measure potential exposure at background locations and areas of known public exposure at and around the Hanford Site.
2. Provide confirmatory information about exposure or potential increases in exposure associated with Hanford Site operations.
3. Where applicable, measure preoperational external radiation levels for new facilities and/or changes in radiation levels during operation of existing facilities.
4. Address needs for DOE to provide public assurance for potential exposure at the site boundary and in nearby communities.
5. Support emergency response in the advent of a radiological release or an accident at the site.
6. Support the evaluation of the effectiveness of site effluent controls and model predictions of offsite dose estimates.

2.1 Principles of Thermoluminescent Dosimetry

The physical principles behind thermoluminescence and the operational aspects of thermoluminescent dosimetry are described in numerous textbooks (Cameron et al 1968; Becker 1973; McKinlay 1981; Oberhoffer and Scharmann 1981; Horowitz 1984; McKeever 1985; Attix 1986; McKeever et al. 1995; Furetta and Weng 1998; Knoll 1999). Brief explanations are presented below as background for this report. For a more detailed understanding of TLD theory and application, the reader is encouraged to explore the references listed above.

Some inorganic phosphors emit light (i.e., fluorescence) when exposed to ionizing radiation. This fluorescence can be immediate or delayed. In some cases, the crystalline forms of these materials store some of the energy imparted to them from ionizing radiation and release that energy as light when the temperature of the crystal is raised. Under carefully controlled conditions of heating, the amount of light produced is directly proportional to the amount of ionizing radiation to which the material was exposed. The reproducibility and linearity of thermoluminescent response are key properties that permit TLD use for measuring ionizing radiation levels in the environment.

Excitation by ionizing radiation (electromagnetic or charged particles) raises the energy level of electrons in the crystalline material from the valence band to the conduction band. At the same time, an electron hole is created in the crystal lattice. In a pure ionic lattice, the electron and hole will quickly recombine, resulting in fluorescence (immediate emission of light). In thermoluminescent material, the lattice has trace amounts of impurity ions of slightly different radii. The ions help create trapping centers where electrons and holes can become temporarily trapped. The energy levels of the trapping centers are below that of the conduction band. When the temperature of the material is raised, the energy levels of the electrons and holes are raised. If they are raised sufficiently to reach the conduction band, the electrons and holes can recombine, resulting in the emission of photons. If the magnitude of the energy difference is about 3 to 4 electron volts (eV), the emitted photon is in the visible region and is the basis of the TLD signal. Ideally, one photon is emitted per trapped carrier and the total number of emitted photons can be used as an indication of the original number of electron-hole pairs created by the radiation. All TLDs operate on this principle, but performance varies between materials and processing methods.

2.2 Operational Considerations

Thermoluminescence was measured by instruments called TLD readers. Environmental TLDs were processed by PNNL or U.S. Testing, a contract laboratory established in Richland in 1965. TLD readers generally consist of a controlled heating system, such as a heated planchet, hot finger, or hot gas stream, and a light-collection and -measurement system, such as a photomultiplier tube (PMT) with lenses and associated circuitry to amplify and quantify the signal. The thermoluminescence signal is the total number of photons counted or the total charge collected within a given time interval in the PMT circuitry while the TLD chip is being heated. The thermoluminescence signal is generally broken into successive small intervals and recorded as a function of time to obtain a "glow curve." When the temperature is gradually raised in a controlled fashion (usually linearly) the release of light may be recorded as a function of temperature. Electron traps with differing energy levels are emptied at different temperatures, thereby producing a glow curve with generally distinct glow peaks. For any given peak, the absorbed dose in the TLD chip is proportional to both the peak height and area. To the extent practicable, only stable peaks with long half-lives (i.e., minimal fading at room temperature) are used for dosimetric purposes. Early TLD readout equipment did not have true glow curve capability. In these systems, the thermoluminescence signal used for dosimetric purposes was simply the light output measured (i.e., PMT charge collected) during the entire heating cycle.

TLD materials have the practical advantage of being reusable. With proper annealing and handling, a single TLD chip may be reused hundreds of times without significant change in its properties or degradation of its performance. TLD material can be "annealed" for reuse by heating to sufficiently high temperature to empty all ion traps and thus erase any existing thermoluminescence signal. Conversely, TLDs have the disadvantage of their dose signal being destroyed by the readout process. The temperatures typically used during readout are sufficiently high that the dose signal is completely removed during the readout process and lost if not recorded with appropriate data-capture devices.

Ideally, the selection of TLD materials and the design of TLD systems (readers and dosimeters) should be made with the objective of optimizing the properties listed below.

- Zero dose reading (background) – This is the lowest reading obtainable from the material and is based on readout shortly after annealing. Contribution to this reading from ambient radiation is assumed to

be negligible. Infrared signal and PMT dark current may be significant contributors. When expressed in units of exposure or dose, this value will be largely a function of the sensitivity of the material.

- Sensitivity (per unit mass, or per chip) – This is simply the amount of light output per unit mass per unit exposure. Because most TLD readers are not calibrated to measure light output directly, the light output for a given reader system is usually expressed in terms of the charge collected on the photomultiplier. For solid chips of a given shape and size, sensitivity is frequently expressed as nanocoulombs per milliroentgen (nC/mR). Manufacturer-quoted values for the sensitivity of calcium fluoride:dysprosium (CaF_2:Dy) and calcium fluoride::manganese (CaF_2:Mn) are about 30 and 10 times that of lithium flouride::magnesium, titanium (LiF:Mg,Ti), respectively. However, sensitivity for a given phosphor depends upon the heating rates and the area of the glow curve that is integrated for dosimetric purposes. When only stable peaks are used for dose determination and/or post-irradiation anneal treatments are used to reduce fading, the sensitivities may be reduced by 50% or more. As implemented in the Harshaw 8807 dosimeter at Hanford, the CaF_2:Dy sensitivity is about 16 times that of the LiF:Mg,Ti sensitivity.
- Reproducibility – This system property is generally expressed as the standard deviation of repeated readout values obtained from the same dosimeter or chip, when given the same dose. This value is generally less than 2% for LiF and generally less than 4% for CaF_2 phosphors (Oberhoffer and Scharmann 1981). Reproducibility depends to a large extent on readout equipment and methods and is generally better with linear heating and with non-contact heating (hot gas or infrared heating). Reproducibility also depends on dose level. Reproducibility at dose levels more than 10 times the zero dose reading will be substantially better than at dose levels at or near the zero dose reading. For this reason, monitoring periods should be selected to ensure a signal that is well above the zero dose reading.
- Detection Threshold – This is the dose level that is significantly different from background and will be reliably detected with the given system.
- Linearity – This is the degree to which the reported and given exposure values agree over the range of dose for which system will be used. At dose levels less than 100 rad, LiF and CaF_2 have very good linearity. Above 100 rad, LiF exhibits supralinear response (over-response).
- Fading – This is the loss of signal with time after irradiation (post-irradiation fading) or loss of sensitivity before irradiation (pre-irradiation fading). The net effect of the two is lower light output per unit exposure with longer times between anneal and readout. Fading may be caused by exposure to light (optical fading) or heat (thermal fading). LiF has much less sensitivity to light than CaF_2. With proper anneal treatment and readout methods, LiF has lower thermal fading than CaF_2.
- Energy Dependence – This is the degree to which the thermoluminescence signal is directly proportional to the value to be measured (exposure or absorbed dose in air or tissue) over the range of radiation energies intended to be measured. LiF has an average atomic number (8.2) that is lower than that of CaF_2:Dy (16.3). As a result, the LiF response to photons is much less energy dependent over the range from 20 keV to 1250 keV.
- Light Sensitivity – This is the degree to which visible light influences the TLD response to radiation or produces its own response in the TLD material. Light sensitivity may take the form of reducing stored signal from exposure received or introducing signal in a chip with no radiation exposure. CaF_2 phosphors exhibit significant light sensitivity whereas LiF does not.

- Moisture Sensitivity – This is the degree to which moisture influences the response of the TLD material to radiation and/or the degree to which the material responds directly to moisture. Both CaF_2 and LiF are relatively insensitive to moisture.

The selection of TLD material must take into account the crystalline structure, or trap depth, and atomic number of the material. Materials such as LiF:Mg,Ti and calcium sulfate:dysprosium ($CaSO_4$:Dy) are better suited for longer-term exposures because of their minimal fading of signal at ambient temperatures. Even though LiF:Mg,Ti is less sensitive than CaF_2:Mn, CaF_2:Dy, and $CaSO_4$:Dy, it has proven to be the most popular because of its low average atomic number (8.2), which is similar to that of air (7.6) or tissue (7.4). The radiation-absorbed dose in LiF is therefore closely correlated with the radiation-absorbed dose in air or tissue, over a wide range of photon energies. For TLD materials with higher atomic number, the enhanced photoelectric interactions exaggerate the response to low-energy photons or x-rays. CaF_2:Mn, for example, has an atomic number of 16.3, and over-responds to 30-keV photons by a factor of 15 and to 70-keV photons by a factor of 8, relative to its response to 1.173- and 1.333-MeV photons from ^{60}Co (Oberhoffer and Scharmann 1981; Knoll 1999).

Because different TLD systems (TLD materials, TLD readers, dosimeter designs, calibration and dose calculation methods, and storage and/or deployment methods) have been used over the years for environmental surveillance at Hanford, it is inappropriate to compare data from one period of time to another without accounting for the potential differences in response for the systems involved. The changes in environmental TLD designs used at Hanford followed developments in the technology and its application to occupational exposure. Initially, chip materials had a greater sensitivity than materials used in later years; however, this was not a significant factor for environmental TLDs.

2.3 Environmental Dosimeter Designs at Hanford

Over the 35 years that TLDs were used for environmental surveillance, several different designs based on phosphor material, number of chips, and shielding were used. All were calibrated to measure exposure in air in units of milliroentgens (mR). From their introduction in 1970 through the end of their deployment in 2005, TLD results were considered equivalent to dose equivalent (1 mR = 1 mrem). TLDs were first deployed in Hanford environs in June 1970 and were collected on a monthly exchange cycle (Corley 1973). During the 1970s, TLDs were primarily processed at a contract laboratory (U.S. Testing); however, PNNL assumed responsibility for environmental TLD processing by 1980.

Because the focus at Hanford was to evaluate contributions to external radiation arising from Hanford operations, the early TLD designs were shielded to remove the lower-energy gamma emissions to control an over-response at the lower range of the energy spectrum. A description of each design used since that time is provided below and summarized in Table 2.1.

- Design 1 – The first environmental dosimeter design used at Hanford was deployed from 1970 through 1976 (Fix et al. 1977). It was made of three CaF_2:Dy (TLD-200) chips encased in a capsule with filters (0.01 inch of tantalum and 0.002 inch of lead). These filters shielded the chips from low-energy gamma photons and beta particles and provided an approximately uniform energy response above 70 keV. This process is referred to as flattening the response. Below 70 keV, the response decreases rapidly because of the shielding. The energy response of this dosimeter when normalized to ^{60}Co (1250 keV) was determined to be ± 30% from 50 keV to 1250 keV (Denham et al. 1972). The equipment used to read TLDs during this time included the Eberline Model TLR-5 and the

Harshaw 2000 reader. The calibration source was ^{137}Cs. The reported exposure from this dosimeter design was taken to be equivalent to absorbed dose in tissue.

Table 2.1. Characteristics of Environmental Dosimetry Systems Used at Hanford

	Design 1	Design 2	Design 3	Design 4
Dosimeter Name	TLD-200	TLD-400	TLD-700	Harshaw 8807
Deployment Timeframe	1970–1976	1977–1989	1990–1994	1995–2005
Phosphor	CaF_2:Dy (TLD-200)	CaF_2:Mn (TLD-400)	^{7}LiF:Mg,Ti (TLD-700)	^{7}LiF:Mg,Ti (TLD-700)
Manufacturer	Harshaw	Harshaw	Harshaw	Harshaw
Detector Form	solid (chip)	solid (chip)	solid (chip)	solid (chip)
Dimensions (mm)	3.2 × 3.2 × 0.9	3 × 3 × 0.9	3 × 3 × 0.9	3 × 3 × 0.9
Detectors per Dosimeter	3	5	12	2
Anneal Procedure (pre-irradiation)	Oven Anneal: 1 h @ 400°C 2 h @ 100°C	Oven Anneal: 1 h @ 400°C 2 h @ 100°C	Reader anneal: 2 read cycles 20 s @ 300°C × 2 Oven anneal: 16 h @ 80°C	Reader anneal: 1 cycle 39 s (14 s @ 300°C) Oven Anneal: 16 h @ 80°C
Anneal Procedure (post-irradiation)	Oven anneal in capsule: 15 min @ 80°C	None	Oven anneal: 30 min @ 80°C	none
TLD Readout Equipment	Eberline Model TLR-5[(a)]/Harshaw 2000	Harshaw 2000 A/B Reader Harshaw 2080 TL Analyzer	Hanford Personnel TLD Readers: Constant temp hot finger	Harshaw 8800 hot gas with linear heating
Readout Procedure	Preheat pan to 90°C for 10 s 90–275°C/15 s	Linear heating: 25–150°C/2 s 150–325°C/18 s integrate glow: 150–280°C	Oven anneal: 30 min @ 80°C Readout: 20 s @ 300°C Integrate glow 20 s	Linear heating: 50-300°C/25 s 300°C/8 s Integrate glow 15 s–30 s (150–300°C)
Encapsulation (outer to inner)	0.1 mm PVC 0.051 mm Pb 0.254 mm Ta	0.1 mm PVC 0.051 mm Pb 0.254 mm Ta 4 mm polystyrene foam	164 mg/cm^2 ABS 12 mg/cm^2 PTFE	80 mg/cm^2 ABS 12 mg/cm^2 PTFE
Calibration Source	^{137}Cs	^{137}Cs	^{137}Cs	^{137}Cs
Approximate Detection Threshold	1 mR	0.1 mR	1 mR	1 mR
Energy Dependence	±30% of ^{60}Co from 50 to 1500 keV	±10% of ^{60}Co from 70 keV to 1250 keV, 25% of ^{60}Co @ 40 keV	±20% from 20 keV to 1250 keV 140% of ^{137}Cs @ 40 keV	±20% from 20 keV to 1250 keV 140% of ^{137}Cs @ 40 keV
Field Cycle	monthly	monthly	quarterly	quarterly
Post Irradiation Fading	est. @ ~12% in 4 weeks	20% in 4 weeks	5%/year	15%/year

Table 2.1. (contd)

	Design 1	Design 2	Design 3	Design 4
Fade correction applied	NA	10% monthly	none	5% quarterly
Bias (B)	NA	0.003	-0.028	0.019
Precision (S)	NA	0.066	0.099	0.041
Reported/Given Exposure (avg)	NA	1.00	0.97	1.02
Reported/Given Exposure (min)	NA	0.47	0.75	0.94
Reported/Given Exposure (max)	NA	1.96	1.20	1.12

(a) Denham et al. 1972.
(b) Likely to have switched to a Harshaw 2000 system between 1972 and 1977.
ABS = Acrylonitrile butadiene styrene.
NA = Not available.
PTFE = Polytetrafluoroethylene.
PVC = Polyvinyl chloride.
TLD = Thermoluminescent dosimeter.

- Design 2 – The second environmental dosimeter design used at Hanford was deployed from 1977 through 1989. It used five CaF_2:Mn (TLD-400) chips encased in an opaque plastic capsule lined with the same shielding provided for the CaF_2:Dy (TLD-200) chips in the first design (Fix et al. 1977, Fix and Miller 1978). The energy response for this dosimeter, when normalized to ^{60}Co was determined to be ±10% from 70 keV to 1250 keV and 25% at 40 keV (Fix and Miller 1978). This dosimetry system was calibrated to exposure in air using a ^{137}Cs photon source. The reported exposure from this dosimeter was taken to be equivalent to absorbed dose in tissue. Post-irradiation fading was determined to be approximately 20% per month for acute exposures. A fade correction of 10% was applied to monthly dosimeters, approximating a mid-cycle acute exposure or chronic exposure over the entire cycle. Field deployments were limited to 1 month to minimize problems associated with fading.

  In March 1981, a shortage of TLD-400 chips occurred and a decision was made to temporarily deploy field dosimeters with three chips instead of five. Three chips were used up through January 1984 when a population of replacement chips had been procured and screened for acceptable responsiveness. Processing also changed with the return to the deployment of five chips. The high and low chip readings were discarded and the dose result was based on the average of the remaining three chips. This change was implemented to reduce the uncertainty in reported exposure caused by variability in the sensitivity of individual chips. A mid-cycle calibration was performed that allowed for the discontinuation of a fade correction in the calculations of dose rate.[1] At some field locations, the dosimeter was exchanged monthly for the first half of the year and quarterly thereafter. At shoreline locations, the dosimeter was exchanged quarterly during the entire year.

Design 3 – The third environmental dosimeter design used at Hanford was deployed for routine surveillance from January 1990 through December 1994. It consisted of a green Noryl® PPO (Modified Polyphenylene Oxide) plastic card containing four LiF (TLD-700) chips and one CaF_2:Dy

[1] Letter from RL Dirkes to SM Groeber, "Replacement of TLD Chips," dated January 30, 1984.

(TLD-200) chip. Each chip was sandwiched between thin sheets of Teflon® that could withstand 300°C temperatures. The cards were of identical shape and dimensions with chip locations identical to the cards used in the Hanford Multipurpose Personnel Dosimeter. As such, the environmental TLD cards were read on the Hanford automatic personnel dosimeter readers, which used contact heating though a single hot finger maintained at a constant 300°C for chip readout. Each card was inserted into a dosimeter holder that was weather proofed by heat sealing inside a polyethylene plastic bag. The dosimeter holder was injection molded from an opaque acrylonitrile butadiene styrene (ABS) plastic that provided 164 mg/cm^2 of filtration. The new design enabled the chips to detect low-energy radiations (low-energy x-ray, gamma photons, and some high-energy beta radiations) that previous designs had shielded with layers of lead and tantalum (Woodruff et al. 1991). Because it had no flattening filter, this dosimeter showed an over-response at energies less than 100 keV, with a maximum over-response of 140% at 40 keV relative to ^{137}Cs. When normalized, the response can be expressed as ±20% from 20 keV to 1250 keV.

Three dosimeters were used at each location. The 12 TLD-700 chips at each location were analyzed to determine the average dose rate. The three TLD-200 chips were analyzed only if a radiological emergency occurred. These dosimeters were deployed on quarterly cycles.

The TLD chips were reader-annealed by reading each chip twice using the standard 20-second readout at 300°C. Following this, each card was oven annealed for 16 hours at 80°C. The effect of this low-temperature oven anneal was to reduce the number of low-temperature (i.e., unstable) traps available for storing radiation-induced thermoluminescence signal. After being returned from the field and being washed with methanol and water, each card was oven annealed for 30 minutes at 80°C. This low-temperature anneal just before readout emptied any unstable traps. The net effect of the pre- and post-irradiation low-temperature annealing was to reduce fading under field conditions to approximately 5% per year.

A significant change with this dosimeter design was the calibration of each element of each dosimeter immediately after each field use. Calibrations were accomplished using a ^{137}Cs photon source. The calibration factor (nC/mR) determined for each chip was applied to the background-corrected field reading obtained from the dosimeter. Although this practice should have reduced the variability of individual chip readings for each dosimeter, the audit dosimeter and field dosimeter data obtained in actual practice did not bear this out.

Although the 12-chip LiF dosimeter was not formally implemented until 1990, it was introduced in January 1987 and co-located with the TLD-400 dosimeter at 20 environmental surveillance locations for 2 years to develop a comparative database before its official implementation. During this co-location trial period, the TLD-400 dosimeter remained on a monthly exchange cycle while the 12-chip dosimeter was exchanged on a quarterly basis.

- Design 4 – The fourth dosimeter design used at Hanford for environmental surveillance was the Harshaw 8807 environmental dosimeter deployed from the beginning of 1995 through 2005. As of this writing, it continues to be used for near-field monitoring and characterization work by Hanford decontamination and decommissioning contractors. However, due to funding constraints, its use by the SESP was discontinued at the end of 2005.

  This dosimeter consists of two TLD-700 chips and two TLD-200 chips. The dimensions of the TLD chips are identical to the chips used in previous environmental dosimeter designs at Hanford (Table 2.1). The LiF chips are sandwiched between 12-mg/cm^2 sheets of Teflon® that are mounted

in aluminum cards with permanent barcode labels. The cards are designed to be processed in the Harshaw Model 8800 automatic TLD readers that are also used for readout of personnel dosimeters at Hanford. The cards are placed in black ABS holders. The TLD-700 chips are shielded by 86-mg/cm^2 ABS plastic and the TLD-200 chips are shielded by 86-mg/cm^2 ABS plastic, 2.5-mm tantalum and 0.05-mm lead. Consistent with past practice, this dosimeter has been used to measure exposure in air. Although this dosimeter has some ability to discriminate photon energy when both the TLD-200 and TLD-700 chips are used, only the two TLD-700 chips are used to calculate dose. Without energy correction, this dosimeter has a maximum over-response of about 40% to photons approximately 40 keV in energy. Because the TLD-700 elements are covered by only 84 mg/cm^2 of plastic, this dosimeter responds to low-energy photons and energetic beta particles (e.g., from ^{90}Y).

Because the Harshaw 8800 TLD reader uses a non-contact heating system (heated nitrogen) and linear heating, the reproducibility of TLD readings was greatly improved over previous reader designs. Because the new system is able to apply chip sensitivity factors to chip readings in real time, the reader is able to maintain tighter process controls by reading quality control cards exposed to known radiation doses, and it shuts down automatically when readings exceed user-specified limits. Cards are prepared for issuance by reader annealing, followed by oven annealing at 80°C for 16 hours. No post-irradiation annealing is performed. With this anneal treatment, post-irradiation fading in the TLD-700 chips is reduced to approximately 10% per quarter.

2.4 Quality Assurance Practices

Quality assurance practices were applied to both the deployment and laboratory aspects of the TLD program. Field deployment involved the establishment of written procedures (e.g., Hanf et al. 2007), locations (Fritz et al. 2009[1] and prior internal versions), and formalized chain-of-custody and data-entry protocols. The laboratory quality assurance program included acceptance testing, process quality control, and blind audit samples.

2.4.1 Acceptance Testing

The manufacturer specifications for the TLD-200, TLD-400, and TLD-700 chips used in the Hanford environmental dosimeters have been as follows: within a procurement batch, all chips have a sensitivity that is within ±30% of the batch mean. Before field use, chips were tested for sensitivity and any that fell outside of this range were rejected. Chips were also checked for acceptable background. In actual practice, the observed relative standard deviation in individual chip sensitivity was typically less than 10% (Fix and Miller 1978) and few chips were rejected. Occasionally, as part of procurement, it would be necessary to specify a batch sensitivity that matched previous procurement batches.

[1] Fritz BG, JA Stegen, GW Patton, and TM Poston. 2009. *Surface Environmental Surveillance Project Locations Manual*. Pacific Northwest National Laboratory, Richland, Washington. (Not publicly available.)

2.4.2 Process Quality Control

Throughout the history of TLD use for environmental surveillance at Hanford, process quality control (QC) has been implemented with the TLD readers to ensure the integrity of the data being generated. Process QC involves interspersing readings of the following periodically between readouts of actual field dosimeters:

- PMT dark current − to provide a measure of PMT background signal in the absence of infrared or visible light
- reference light − a light source that provides a measure of PMT sensitivity that includes optics (lenses, filters, etc.)
- un-dosed control dosimeters − to provide a measure of system background that includes the infrared signal from the heating system and intrinsic chip background signal from the chip
- dosed control dosimeters − to provide a measure of overall system sensitivity that includes heating system, light collection and measurement, and phosphor sensitivity.

If these readings were outside of established limits, the process would be halted until the cause could be determined and/or the reader response brought back within limits.

2.4.3 Routine Blind Audit Dosimeters

A blind audit program was administered from late 1979 through the end of 2005. This program was one in which dosimeters prepared for field issue were randomly selected and later exposed to known doses at about mid-cycle or at multiple points throughout the field cycle. The dosimeters that had been exposed were unknown to the laboratory staff processing them. In later years (1990s through 2005), the blind audit program was administered independently for the SESP by a PNNL quality assurance engineer. Audit dosimeters were exposed in the 318 Radiological Calibrations Facility to sources that are traceable to the National Institute of Science and Technology (NIST) in radiation fields calibrated with NIST-traceable ionization chambers. Delivered doses were varied to approximate typical environmental dose rates measured at Hanford. Approximately 30% of the dosimeters selected to be blind audits were left unexposed and used as controls.

For each exposed blind audit dosimeter, a performance quotient, P_i, was calculated as follows:

$$P_i = (\text{Reported exposure} - \text{Given exposure})/\text{Given exposure}$$

Performance quotients for individual audit dosimeters from 1980 through 2005 are plotted in Figure 2.1. For any grouping of dosimeters, the bias (B) and precision (S) of the reported doses can be calculated to provide a measure of the system's accuracy. Bias is calculated as the average of the individual P_i. The precision is calculated as the standard deviation of the individual P_i. Figure 2.2 shows the calculated bias B for each exchange period (monthly or quarterly) from 1980 through 2005. When comprised of large representative samples, the value of S can be used as a measure of the system's combined fractional uncertainty, excluding the uncertainty from transit and storage exposure corrections and fade corrections (arising from temperature variations in the field). The values of B and S for each dosimetry system, calculated from all audit dosimeter data available for that system, are given in Table 2.1. The calculated mean response (reported exposure/given exposure) is also listed. The

calculated values of B and S for each calendar year from 1980 through 2005 are plotted in Figure 2.3. The values of S are plotted as error bars. When B and S are calculated from all 867 audit dosimeter performance quotients available from 1980 through 2005, the bias B for Hanford TLD results is negligible. The overall precision S=0.067 suggests that 95% of reported TLD results at Hanford are within ±15% of the true value.

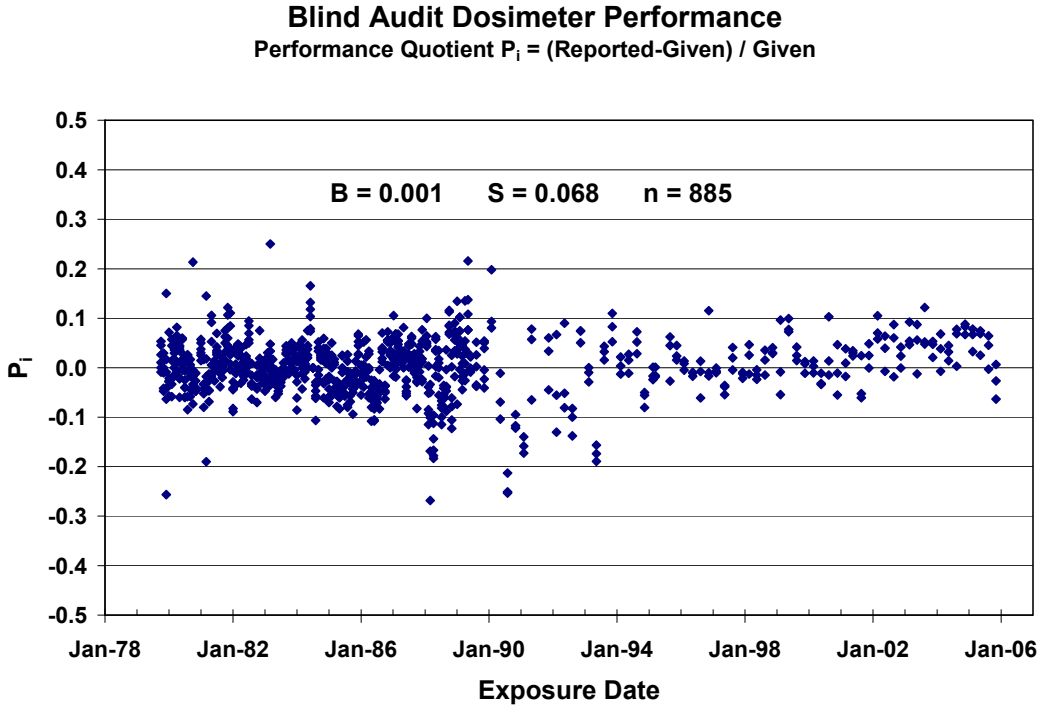


Figure 2.1. Performance Quotients for Individual Audit Dosimeters from 1980 Through 2005

2.4.4 Field and Laboratory Intercomparison Studies

Studies comparing the response of various environmental dosimeter designs under both field and laboratory conditions have been conducted over the years by government and quasi-government agencies. Intercomparisons of this type hosted by other labs provide an objective and independent means of assessing and comparing dosimeter performance. At the time of this writing, the results of PNNL participation in intercomparisons dating from 1991 and summarized in Table 2.2 were available in PNNL project files (Card et al. 1992;[1] Klemic et al. 1995, 1998, 1999). The LiF-based Hanford dosimeter designs used in these intercomparisons (designs 3 and 4) generally responded within ±10% of the reference value established for the tests. One notable exception to the generally good performance is an approximately 50% positive bias in the response of design 3 to ^{226}Ra in the Pacific Northwest Environmental TLD Intercomparison (Card et al. 1992).[1] A similar positive bias was manifested by the other LiF dosimeter in that study that was submitted by the Washington State Department of Health (WDOH). Both of these dosimeters had thin plastic cases and no metal filtration. The over-response could be due to

[1] Card CJ, AW Endres, and RL Buschbom. 1992. "Results of the 1991 Environmental Radiation Quality Assurance Task Force of the Pacific Northwest Thermoluminescent Dosimeter Intercomparison," September 15, 1992 (Washington Public Power and Supply System, Richland, Washington).

the presence of low-energy photons in the emission spectrum of ^{226}Ra. However details about the construction of the source or its spectrum are not known, so the degree to which the high bias is due to energy-dependent characteristics of the dosimeter design cannot be determined.

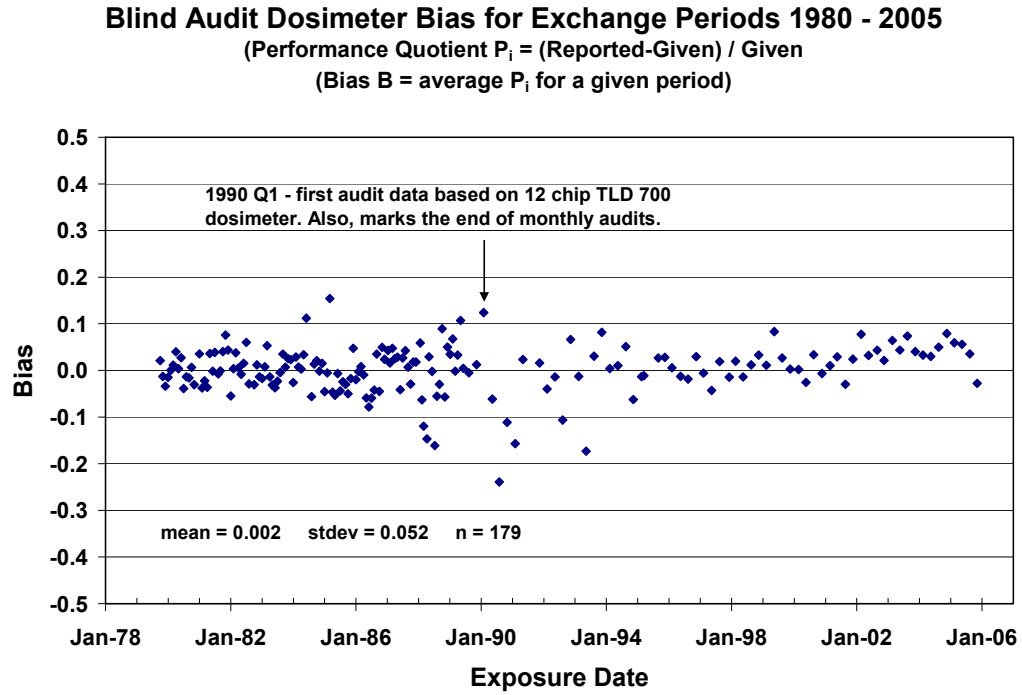


Figure 2.2. Audit Dosimeter Bias B for Exchange Periods from 1980 Through 2005

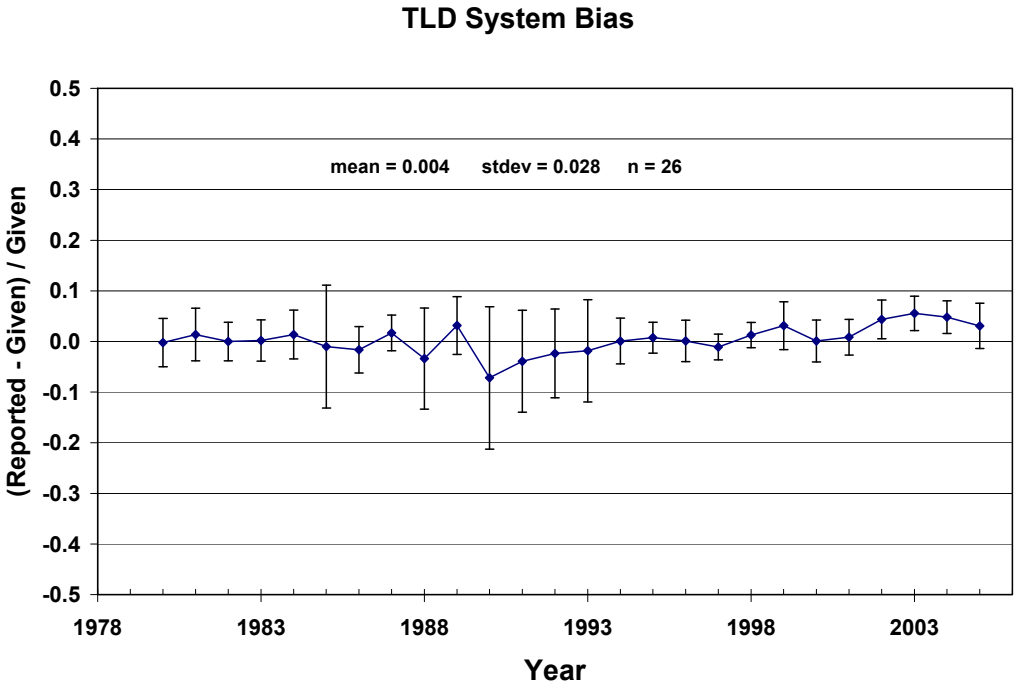


Figure 2.3. TLD System Annual Bias Based on 25 Years of Blind Audit Dosimeter Testing

Table 2.2. Results of TLD Intercomparison Studies

Intercomparison Name	Year	Host	Design	Category	Source	Average Energy (keV)	Quantity	Units	Delivered	Bias B
Pacific Northwest Environmental TLD Intercomparison[a]	1991	Energy NW	3	Cs-137 low dose	Cs-137	662	exposure	mR	30.2	0.04
			3	Cs-137 high dose	Cs-137	662	exposure	mR	105.5	0.00
			3	Ra-226 high dose	Ra-226	700	exposure	mR	95.9	0.56
			3	Ra-226 low dose	Ra-226	700	exposure	mR	18.7	0.55
10th International Intercomparison of Environmental Dosimeters[b]	1993	EML	3	Field	outdoor ambient	NA	air kerma	µGy	237	0.00
			3	Lab Gamma (low)	Cs-137	662	air kerma	µGy	227	-0.07
			3	Lab Gamma (high)	Cs-137	662	air kerma	µGy	637	-0.07
11th International Intercomparison of Environmental Dosimeters[c]	1996	EML	4	Field	outdoor ambient	NA	air kerma	µGy	167	-0.04
			4	Lab Cs	Cs-137	662	air kerma	µGy	511	0.01
			4	Lab Am (blind)	Am-241	59	air kerma	µGy	356	0.12
			4	Lab Am (source known)	Am-241	59	air kerma	µGy	356	0.12
ANSI N13.29 Pilot Test[d]	1997	EML	4	Accident Photon	Cs-137	662	absorbed dose in deep tissue D(10)[e]	mGy	19.2 to 373.2[f]	0.01
			4	Accident Beta	Sr-90/Y-90	931	absorbed dose in shallow tissue D(0.07)[e]	mGy	23.3 to 227.8[f]	-0.07
			4	Routine Photon	Cs-137	662	ambient dose equivalent H*(10)[e]	mSv	0.32 to 5.30[f]	0.02
			4	Routine Beta	Sr-90/Y-90	931	directional dose equivalent H'(0.07,0)[e]	mSv	0.34 to 9.02[f]	-0.10
			4	Energy x-ray H40	H40 filtered x-rays	33	H*(10) and H'(0.07,0)[e]	mSv	0.29 to 4.86[f]	0.05
			4	Energy x-ray H100	H100 filtered x-rays	83	H*(10) and H'(0.07,0)[e]	mSv	0.22 to 5.39[f]	0.07
			4	Environmental Chamber (begin cycle irradiation)	Cs-137	662	H*(10)[e]	mSv	0.51 to 3.18[f]	-0.09

Table 2.2. (contd)

Intercomparison Name	Year	Host	Design	Category	Source	Average Energy (keV)	Quantity	Units	Delivered	Bias B
ANSI N13.29 Pilot Test[d] (contd)			4	Environmental Chamber (mid cycle irradiation)	Cs-137	662	H*(10)[e]	mSv	0.56 to 4.52[f]	-0.11
			4	Environmental Chamber (end cycle irradiation)	Cs-137	662	H*(10)[e]	mSv	0.88 to 2.85[f]	-0.05
12th International Intercomparison of Environmental Dosimeters[g]	2000	EML	4	Lab Cs	Cs-137	662	air kerma	µGy	391	0.00
			4	Field	outdoor ambient	NA	air kerma	µGy	161	-0.06
			4	Field + Cs-137 begin cycle	outdoor ambient + Cs-137	NA	air kerma	µGy	548	-0.01
			4	Field + Cs-137 mid cycle	outdoor ambient + Cs-137	NA	air kerma	µGy	391	0.03
			4	Field + Cs-137 end cycle	outdoor ambient + Cs-137	NA	air kerma	µGy	623	0.01

ANSI = American National Standards Institute.
EML = Environmental Measurements Laboratory.
NA = Not available.
TLD = Thermoluminescent dosimeter.
(a) Card CJ, AW Endres, and RL Buschbom. "Results of the 1991 Environmental Radiation Quality Assurance Task Force of the Pacific Northwest Thermoluminescent Dosimeter Intercomparison," September 15, 1992, Washington Public Power Supply System, Richland, Washington.
(b) Klemic et al. 1995.
(c) Klemic et al. 1999.
(d) Klemic et al. 1998.
(e) Special algorithms and calibrations were required to measure the quantities used in this study.
(f) Ambient dose equivalent H*(10).
(g) Individual results were reported to participants by EML. A formal report analyzing collective results of the intercomparison has not been published.

The Harshaw 8807 dosimeter, which also uses LiF elements with minimal filtration (design 4) did not exhibit a high bias in the x-ray categories of the American National Standards Institute (ANSI) N13.26 Pilot Test (Klemic et al. 1998). However, this is due to the use of special energy-discrimination capabilities in the 8807 algorithm made possible by the dual phosphor design of the dosimeter. This energy-correction capability of the 8807 was not used in routine environmental monitoring at Hanford. It should also be noted that in the ANSI N13.29 Pilot Test, the 8807 dosimeter performed well under the extremes of temperature and humidity applied in the environmental chamber tests that were part of the pilot test. The performance was well within the acceptable limits established for the standard. Unfortunately, none of the intercomparison studies for which Hanford participation data are available encompassed design 2, or the time period from 1985 through 1990, during which the large increases in field results were observed.

2.4.5 Comparison of the TLD and PIC

During calendar year (CY) 1996, pressurized ionization chamber (PIC) measurements were made at four offsite sampling locations where quarterly TLDs were also located. Monthly PIC data were averaged and compared with the TLD results for the same quarter. The data are summarized in Table 2.3 and described in greater detail in the Hanford Site 1996 Environmental Report (Dirkes and Hanf 1997). The PIC data were not available for some months, due to power failures, equipment failures, or other reasons. The TLD results were in reasonable agreement with the PIC results. The mean and standard deviation of the TLD/PIC ratios observed for the entire year were 1.05 and 0.03, respectively. The apparent 5% over-response of the TLD relative to the PIC is attributable to the presence of photons <100 keV in the environmental radiation at these locations, and the known over-response of TLD-700 to photons in this energy range.

Table 2.3. Comparison of PIC and TLD Measurements at Offsite Locations in CY 1996

Location	1996 Quarter	TLD (μR/h)	PIC (μR/h)	TLD/PIC
Leslie Groves Park	1	9.2	8.7	1.06
	2	9.0	8.4	1.08
	3	9.0	8.3	1.08
	4	8.9	8.6	1.03
Basin City School	1	8.7	8.3	1.04
	2	9.0	8.2	1.09
	3	8.9	8.2	1.09
	4	8.7	8.1	1.07
Edwin Markham School	1	9.1	8.7	1.05
	2	8.8	ND	ND
	3	8.3	ND	ND
	4	8.5	8.7	0.98
Heritage College	1	8.5	ND	ND
	2	8.2	7.8	1.05
	3	8.2	7.9	1.04
	4	7.8	7.5	1.04
			Average	1.05
			SD	0.03

ND = No data due to equipment failure or power outages.
PIC = Pressurized ionization chamber.
SD = Standard deviation.
TLD = Thermoluminescent dosimeter.

3.0 Analysis of Environmental TLD Results from 1970 Through 2005

The Hanford Environmental Surveillance TLD Program conducted by PNNL monitored areas defined as the "far field," essentially at the facility fence line and beyond to sampling locations on and off the Hanford Site. To complement the far-field sampling, both effluent and "near-field" facility (within facility fence lines) monitoring with TLDs was conducted concurrently by Hanford Site operational contractors. The near-field data, however, are not evaluated in this report. Results from both monitoring programs are reported annually in site reports that can be accessed electronically (e.g., http://hanford-site.pnl.gov/envreport/).

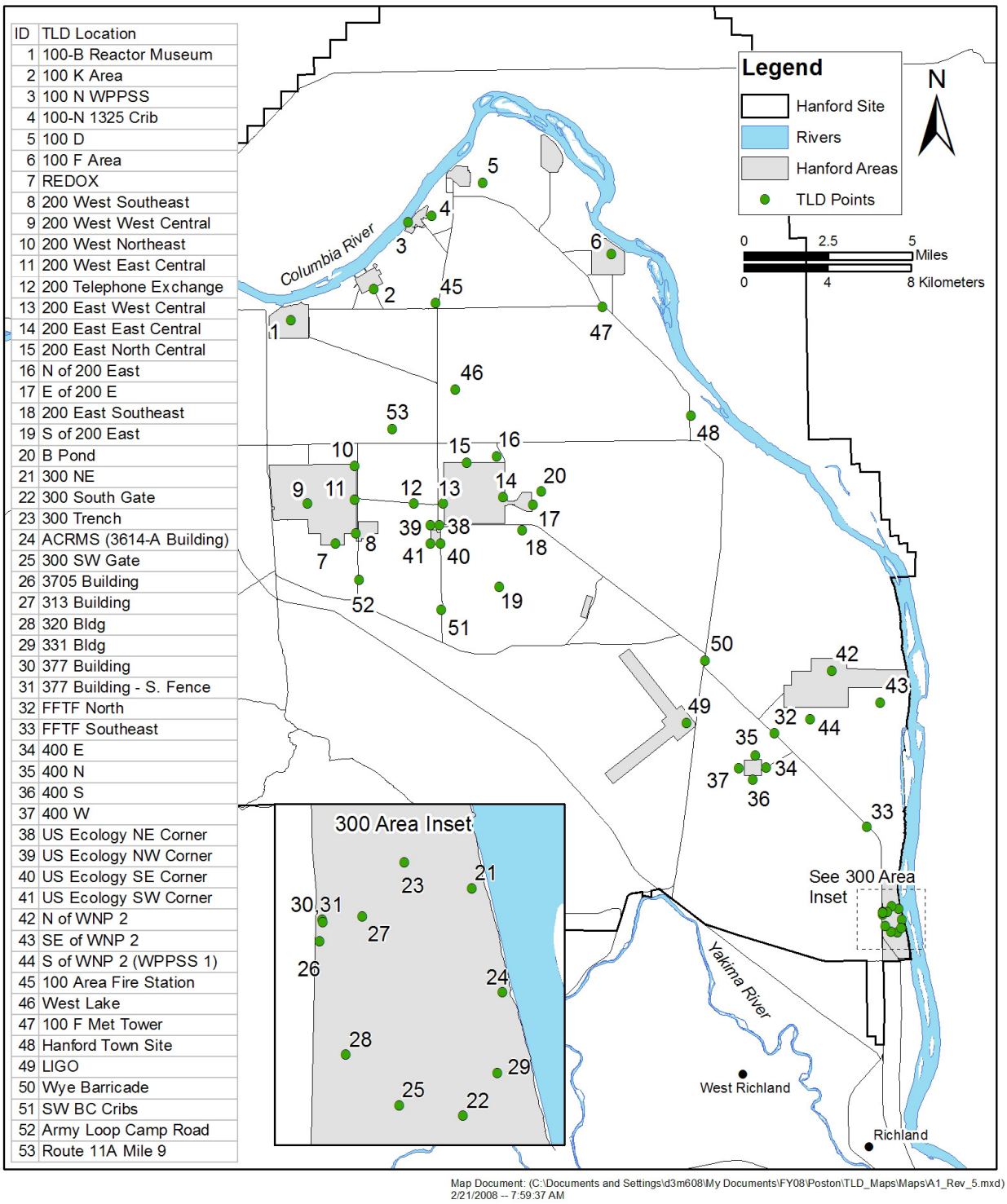
3.1 Environmental TLD Monitoring Activities

Initially, TLDs were deployed at established air surveillance sites on and off the Hanford Site. The site mission was changing from the phase-out of the single-pass plutonium production reactors from 1965 through 1971 and operation of N Reactor, to cleanup and restoration commencing in 1990. With these changes the need for, and the extent of, deployment of TLDs also changed. Some stations remained in operation throughout the entire 35-year period, whereas others operated for periods as short as 3 years. At the time the TLDs were deployed for environmental surveillance, their evaluation followed the design applied to air samplers consisting of perimeter and southeast quadrant regions. The grouping of dosimeter surveillance locations changed in 1978 with the basic establishment of four groupings: onsite, perimeter, community, and distant (Bisping 2005). At the conclusion of the Hanford Environmental Surveillance TLD Program in 2005, TLDs were deployed at 33 onsite locations within the boundaries of the Hanford Site (Figure 3.1), or by distance classification based on their proximity to the Hanford Site perimeter (11 sites, Figure 3.2), and nearby and distant community locations (9 sites, Figure 3.3) (Bisping 2005). TLDs located along the shoreline of the Columbia River (Figure 3.4) were subdivided into two groups. One group consisted of sites located along the Columbia River shoreline at approximately 1-mile intervals from the Vernita Bridge to Kennewick. The other group, located along the 100-N Area shoreline, was established to specifically monitor elevated dose rates associated with operations at the 100-N Area.

3.2 Deployment and Retrieval of Field TLDs

In practice, once the TLDs were obtained from the calibrations laboratory, they were transported to the sampling locations and deployed. For QC purposes, prepared TLDs were shielded during storage and transported in lead vessels to control inadvertent exposure to ionizing radiation. Chain of custody was managed with trip sheets that listed all environmental samples collected on a sampling trip. In the field, TLDs were attached to a metal post or fence and exchanged on a monthly or quarterly schedule. TLD surveillance quickly expanded to include locations along the Columbia River shoreline. A limited number of TLDs were also submerged in the river to measure ionizing radiation fields under water.

The TLD data obtained from the Hanford Environmental Information System (HEIS 1989) database, a repository for data gathered during environmental surveillance activities at the Hanford Site, were sorted by location and plotted as scatter plots (see Appendices A and B). Statistical analyses were



ID	TLD Location
1	100-B Reactor Museum
2	100 K Area
3	100 N WPPSS
4	100-N 1325 Crib
5	100 D
6	100 F Area
7	REDOX
8	200 West Southeast
9	200 West West Central
10	200 West Northeast
11	200 West East Central
12	200 Telephone Exchange
13	200 East West Central
14	200 East East Central
15	200 East North Central
16	N of 200 East
17	E of 200 E
18	200 East Southeast
19	S of 200 East
20	B Pond
21	300 NE
22	300 South Gate
23	300 Trench
24	ACRMS (3614-A Building)
25	300 SW Gate
26	3705 Building
27	313 Building
28	320 Bldg
29	331 Bldg
30	377 Building
31	377 Building - S. Fence
32	FFTF North
33	FFTF Southeast
34	400 E
35	400 N
36	400 S
37	400 W
38	US Ecology NE Corner
39	US Ecology NW Corner
40	US Ecology SE Corner
41	US Ecology SW Corner
42	N of WNP 2
43	SE of WNP 2
44	S of WNP 2 (WPPSS 1)
45	100 Area Fire Station
46	West Lake
47	100 F Met Tower
48	Hanford Town Site
49	LIGO
50	Wye Barricade
51	SW BC Cribs
52	Army Loop Camp Road
53	Route 11A Mile 9

Figure 3.1. Onsite Surveillance TLD Locations, 1970–2005

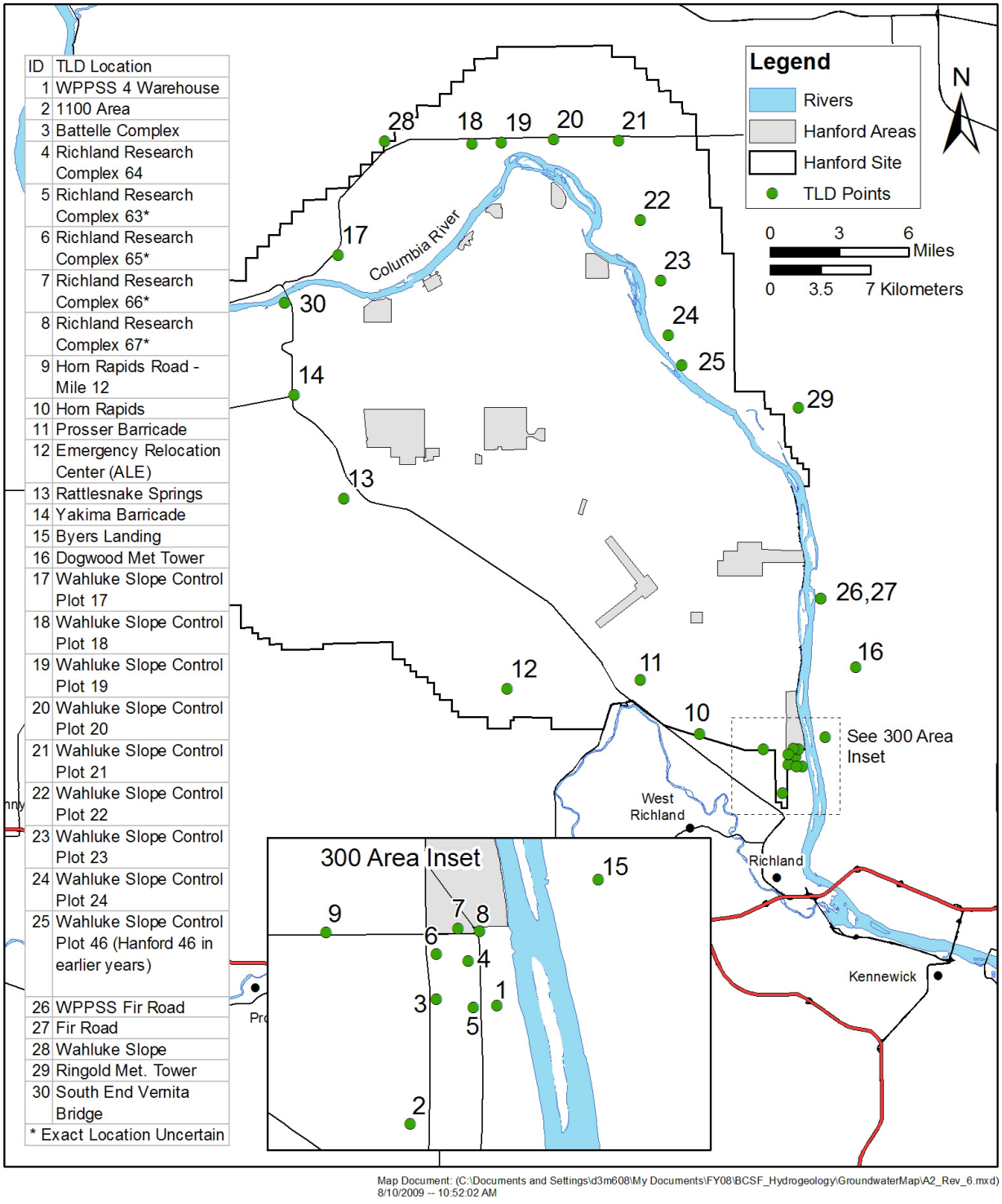
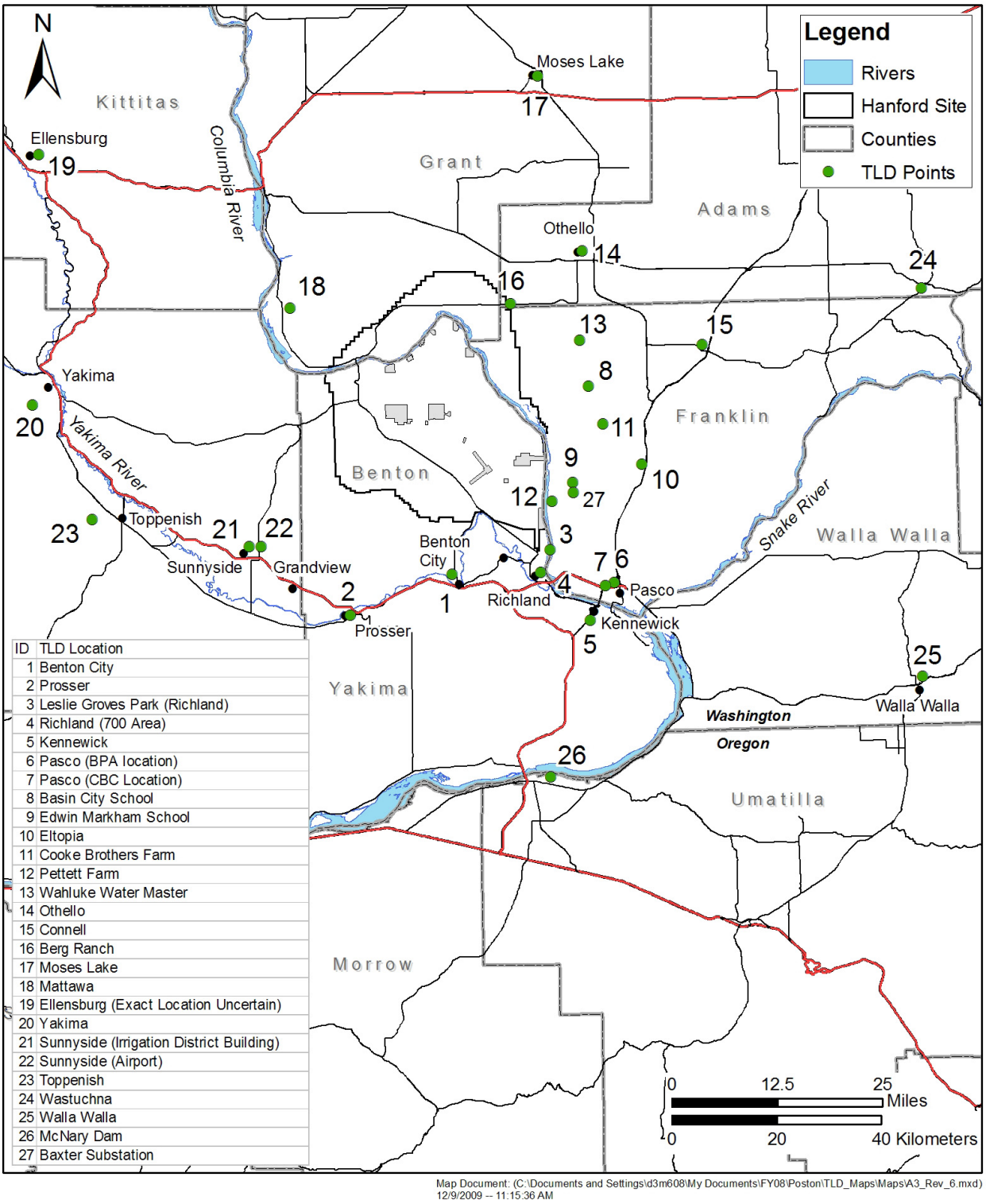
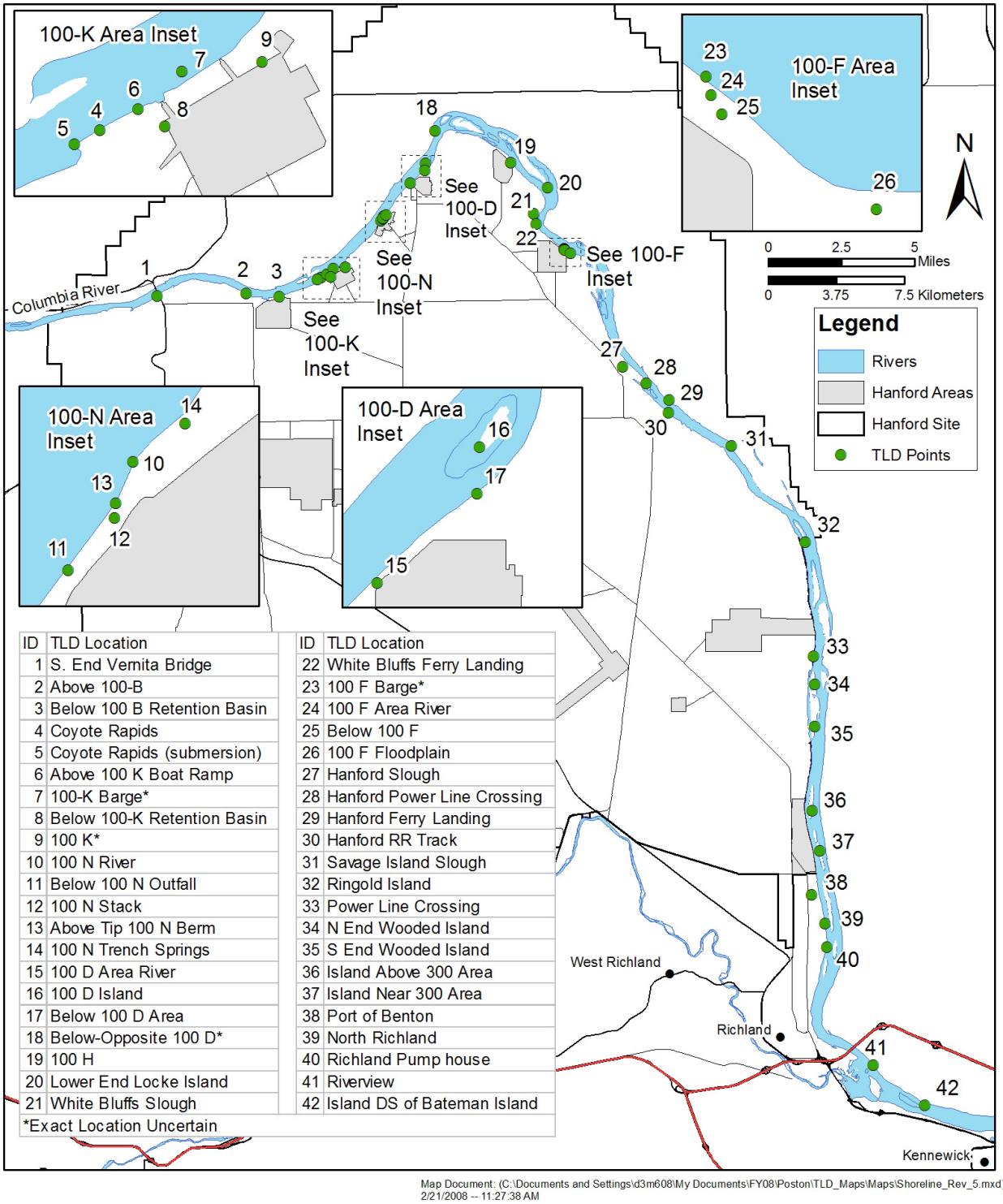


Figure 3.2. Perimeter Surveillance TLD Locations, 1970–2005



ID	TLD Location
1	Benton City
2	Prosser
3	Leslie Groves Park (Richland)
4	Richland (700 Area)
5	Kennewick
6	Pasco (BPA location)
7	Pasco (CBC Location)
8	Basin City School
9	Edwin Markham School
10	Eltopia
11	Cooke Brothers Farm
12	Pettett Farm
13	Wahluke Water Master
14	Othello
15	Connell
16	Berg Ranch
17	Moses Lake
18	Mattawa
19	Ellensburg (Exact Location Uncertain)
20	Yakima
21	Sunnyside (Irrigation District Building)
22	Sunnyside (Airport)
23	Toppenish
24	Wastuchna
25	Walla Walla
26	McNary Dam
27	Baxter Substation

Figure 3.3. Nearby and Distant Community Surveillance TLD Sites, 1970–2005



ID	TLD Location	ID	TLD Location
1	S. End Vernita Bridge	22	White Bluffs Ferry Landing
2	Above 100-B	23	100 F Barge*
3	Below 100 B Retention Basin	24	100 F Area River
4	Coyote Rapids	25	Below 100 F
5	Coyote Rapids (submersion)	26	100 F Floodplain
6	Above 100 K Boat Ramp	27	Hanford Slough
7	100-K Barge*	28	Hanford Power Line Crossing
8	Below 100-K Retention Basin	29	Hanford Ferry Landing
9	100 K*	30	Hanford RR Track
10	100 N River	31	Savage Island Slough
11	Below 100 N Outfall	32	Ringold Island
12	100 N Stack	33	Power Line Crossing
13	Above Tip 100 N Berm	34	N End Wooded Island
14	100 N Trench Springs	35	S End Wooded Island
15	100 D Area River	36	Island Above 300 Area
16	100 D Island	37	Island Near 300 Area
17	Below 100 D Area	38	Port of Benton
18	Below-Opposite 100 D*	39	North Richland
19	100 H	40	Richland Pump house
20	Lower End Locke Island	41	Riverview
21	White Bluffs Slough	42	Island DS of Bateman Island

*Exact Location Uncertain

Map Document: (C:\Documents and Settings\d3m608\My Documents\FY08\Poston\TLD_Maps\Maps\Shoreline_Rev_5.mxd)
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Figure 3.4. Shoreline Surveillance TLD Locations, 1970–2005

performed to identify significant differences among groups of data. Analysis of variance (ANOVA) was performed based on dosimeter type (within each distance classification) and distance class. The results are presented as bar graphs showing means and with 95% confidence intervals. The ANOVA addressed two questions. One null hypothesis was that there was no difference in TLD readings based on dosimeter type. The second null hypothesis was that there was no difference between location groupings of TLDs (i.e., onsite, perimeter, community, or distant). Finally, to evaluate an apparent increase in dose rates within the PNNL data, a comparison was made between PNNL surveillance data and WDOH data collected from 1985 through 1989 at two offsite locations. Data for that time period were divided into three discrete sampling periods, and analyzed by ANOVA followed by Scheffé's multiple comparison tests for differences in sampling means. All statistical analyses were performed with Excel or Statview software.

3.3 General Observations

Observations made during the initial test deployment, the ensuing routine deployment, and dose rates by location grouping are summarized here.

3.3.1 Initial Test Deployment (1970)

TLDs were first deployed at Hanford in June 1970 and the data were reported in the environmental surveillance report for that year (Corley 1973). These data were not entered into HEIS and are briefly summarized here to complete the record. The design 1 TLDs were deployed at all offsite air-monitoring locations as part of an initial test to evaluate the use of TLDs to replace measurements conducted with PICs. Only mean, maximum, and minimum dose rates were reported for perimeter and southeast air-surveillance quadrants (Table 3.1). This initial deployment was experimental and full deployment was initiated in 1971. All TLD data collected from 1971 through 2005 were placed in HEIS.

Table 3.1. Experimental Exposure Rates (mR/d) Obtained from the Initial TLD Field Deployment in 1970 Around the Hanford Site (Corley 1973)

Location Group	Minimum	Maximum	Mean
Perimeter Communities[(a)]	0.10	0.32	0.16
Southeast Quadrant[(b)]	0.11	0.24	0.17

(a) These communities included Walla Walla, NcNary Dam, Wastuchna, Moses Lake, Ellensburg, Sunnyside, Othello, and Connell (taken from Table 11, Corley 1973).
(b) These locations included Berg Ranch, Wahluke Watermaster, Wahluke Slope, Eltopia, Ringold, Byer's Landing, Richland, Pasco, Kennewick, and Benton City (taken from Table 11, Corley 1973).

In 1972, sites were identified specifically for the deployment of TLDs. When initially deployed, the onsite and surrounding areas were partitioned into quadrants. Offsite TLDs were grouped into perimeter locations that were more than 10 miles from the Hanford Site boundary. Offsite locations classified as the southeast quadrant were located along the site boundary and within about 10 miles of the site boundary. This configuration was established when the site was in full production of plutonium and reflects a greater concern for potential offsite exposure. With the cessation of single-pass reactor operations from 1965

through 1971, a greater focus on areas close to the site was adopted. Perimeter, community, and distant location designations were adopted for offsite surveillance objectives in 1976. This basic grouping persisted through 2005; however, over the years, some stations were dropped and others were added based on surveillance needs and the nature of site operations at the time.

3.3.2 Routine Deployment, 1971–2005

As an example of the general trends in TLD response, data for Byer's Landing from 1971 through 2005 are presented in a scatter plot (Figure 3.5). When TLDs were first deployed in 1970, fallout from foreign nuclear weapons tests in the atmosphere influenced dose rates measured at Hanford (Corley et al. 1970). In 1970, nine nuclear weapons tests were conducted, eight by France and one by China (Norris and Arkin 1996). After 1970, nuclear weapons testing continued by France and China, but generally ceased after 1980. Hanford Site TLDs may have been influenced by the nuclear weapons testing conducted immediately post-1970 by France and China. These observations also were corroborated by gross beta values (Figure 3.5); however, the slight increases observed are not so obvious in the TLD-derived dose rates from areas adjacent to fuel reprocessing and waste management areas that had elevated background radiation levels associated with site operations. These slight elevations in dose rate waned after 1971 and reported dose rates generally held constant through 1985. With the deployment of the Harshaw TLD-400 series beginning in 1977, initial results matched the results observed over the following 5 years and generally held constant up to 1985. Starting in 1985, there was a systematic increase in reported dose rates as well as increased variability among TLD readings through the next 10 years to 1995. The upward trend in dose rates from the beginning of 1985 through 1989 was generally observed at all TLD monitoring locations during that timeframe and represents an approximate 30 to 40% increase over dose rates measured from 1973 through 1984. This apparent increase in external dose rates was not believed to be attributable to operations at Hanford based on surveillance data for other environmental media at that time. On the contrary, site scientists were aware that the TLD design that was deployed at Hanford was producing results that were lower than the results recorded by the Washington Department of Social and Health Services, the predecessor agency to the WDOH. U.S. Testing, the contract laboratory that was processing TLDs, was also having difficulty meeting recently adopted QC guidelines imposed by DOE (J. Fix, personal communication). At that time, DOE had implemented a laboratory accreditation program that was more focused on personnel dosimetry than on environmental dosimetry. Dosimeter processing was transferred to PNNL beginning in October 1988 to better manage the dosimetry programs.

To evaluate the apparent increase in external dose rates, PNNL CaF_2:Mn TLD results were compared to TLD data collected and analyzed by WDOH in its independent oversight program. An analysis of PNNL audit data for the period from 1985 through 1989 indicated a similar increase in bias. During this time period, the WDOH deployed Harshaw 100 (LiF) TLDs (WDOH no date a, b, c, d, e). The design consisted of four chips per card, two cards per TLD package, for a total of eight chips per package. The TLDs were analyzed on a Harshaw 2271 counter. Data from two co-located offsite locations were selected for statistical comparison of WDOH and PNNL data: Moses Lake and Connell. For both data sets, TLD results were reported in units of mR/day.

Operationally, other minor differences existed between the two TLD programs. The WDOH TLDs were deployed on a quarterly basis and the PNNL TLDs were deployed on a monthly basis. PNNL TLDs at the Moses Lake site had been deployed on both a monthly and a quarterly schedule for part of the

1985–1989 timeframe. To evaluate the effects of a longer deployment time, the PNNL Moses Lake data were subjected to a two-tailed t-test under the null hypothesis that there was no difference in daily dose rates based on the duration of deployment. The analysis indicated no significant difference between deployment duration (P=0.750) and supported the direct comparisons between WDOH quarterly and PNNL monthly data.

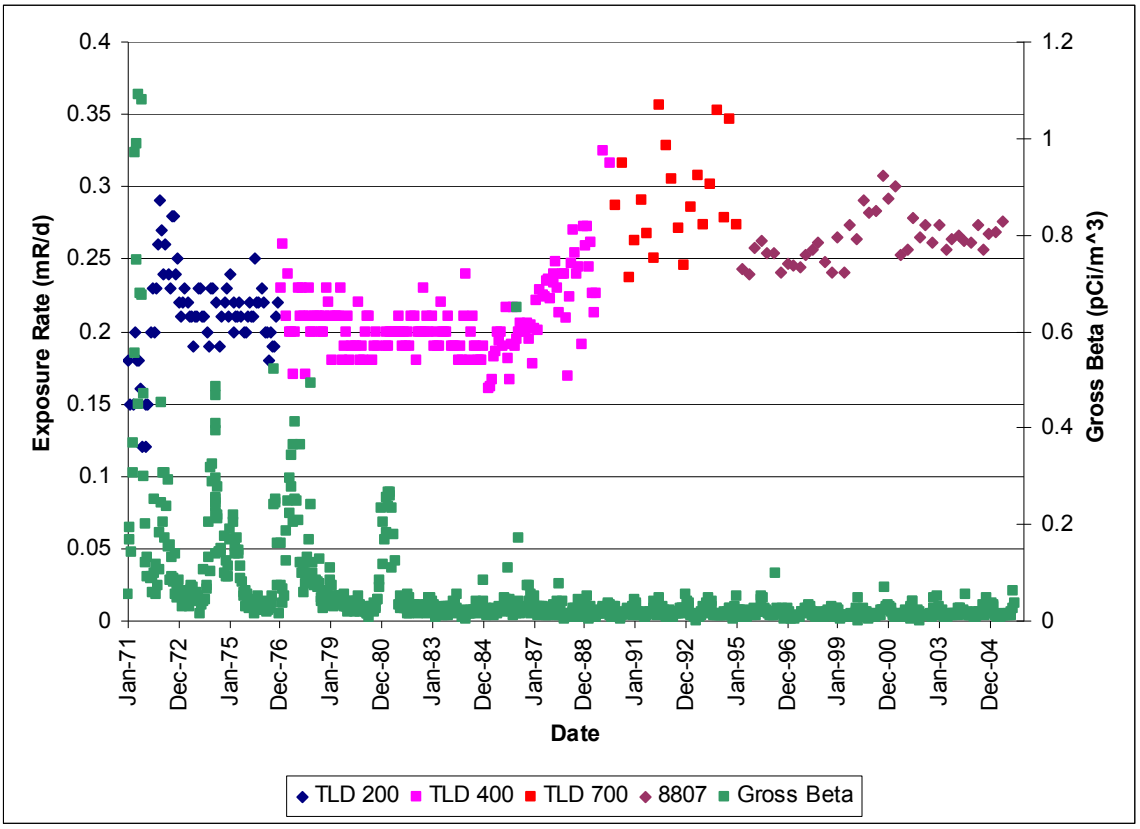

Figure 3.5. Results of Dosimeter Readings by Dosimeter Type and Gross Beta Readings in Air at the Byer's Landing Location, 1971–2005

The statistical analysis evaluated design 2 (5 x 400 Series) TLDs deployed monthly by PNNL from 1985 through 1989 and compared the results to WDOH data deployed over the same time period but collected on a quarterly schedule. Three sequential, but unequal study periods, were identified and analyzed by ANOVA and Scheffé's multiple comparison test for differences in mean daily dose rate (Table 3.2). For the WDOH data, there was no significant difference between the three study periods and no consistent trend in estimated dose rate. For the PNNL data, mean daily dose rates increased by 33% at Connell and 37% at Moses Lake from the first study period (1985–1986) through the third study period (1989−1990; $P < 0.001$). The 1989 data had been processed by PNNL personnel, while data generated prior to October 1988 had been processed by U.S. Testing. Comparatively, in the first study period, PNNL estimates of external radiation were lower than those generated by the WDOH. This potential effect was not noted in annual reports (e.g., Jaquish and Bryce 1990) because the basis of analysis was by major site grouping (offsite, perimeter, etc.), and the sampling error quickly overshadowed the analytical error that was apparent for these two offsite locations.

Table 3.2. Comparison of State and PNNL TLD Data and Scheffé's Multiple Comparisons of Means for Connell and Moses Lake Data

Study Period	Dates[a]	State		Pacific Northwest National Laboratory	
		Mean (± 2 SEM)[b]	Scheffé's[b]	Mean (± 2 SEM)[b]	Scheffé's[b]
Connell (mR/day)					
Conn1	Jan 85–Oct 86	0.222±0.024 (n=8)	x	0.163±0.006 (n=18)	s
Conn2	Jan 87–Oct 88	0.206±0.016 (n=7)	x	0.203±0.014 (n=30)	t
Conn3	Jan 89–Oct 90	0.222±0.018 (n=8)	x	0.219±0.020 (n=11)	t
Moses Lake (mR/day)					
ML1	Jan 85–Oct 86	0.183±0.010 (n=7)	g	0.144±0.006 (n=23)	j
ML2	Jan 87–Oct 88	0.200±0.028 (n=7)	g	0.192±0.008 (n=26)	k
ML3	Jan 89–Oct 90	0.181±0.010 (n=8)	g	0.197±0.036 (n=7)	k

(a) Grouped by state quarterly sample collection dates
(b) Mean dose rate values (mR/d) followed by the same letter are not significantly different for Scheffé's multiple comparison test ($P < 0.05$).
SEM = Standard error of the mean.

An examination of TLD processing records and procedures did not suggest a specific cause for the increase in Hanford TLD readings. PNNL TLD performance data were reviewed and analyzed for the 1985–1989 study period. Performance data collected for PNNL data were grouped by the same study periods used to compare Moses Lake and Connell data. This analysis demonstrated an increase in bias and P_i for the third study period compared to the first study period (Table 3.3). These observations of changes in mean performance quotient or bias calculations were significant for Moses Lake and Connell ($P < 0.05$). The change in the QC data was of insufficient magnitude to account for the 30 to 40% increase in reported external dose rates between 1985 and 1990. As discussed previously, the gradual change over this 5-year period may be attributable to a gradual change in the sensitivity of the field chip population relative to the calibration chip population and/or audit chip population. This may have been facilitated by the introduction of additional new TLD chips to replace broken or lost chips, or a change in calibration practices associated with changes in lab equipment or staff.

It should be noted that there was a large-scale turnover in TLD-400 chips in 1983 as a result of internal contamination found in some of the TLD-400 chips that resulted in their removal from use in 1981[1] and increasing demand for more chips onsite by PNNL and other site contractors. Significant efforts were made to procure and screen the new chips to standardize the range of responsiveness in the population of chips used for surveillance.[2] This occurrence in part led to the decision to increase the

[1] Memo, DM Fleming to MJ Sula, "Contamination of Environmental Dosimeters," dated February 18, 1981.
[2] Memo, MJ Sula to DM Fleming, "PNL Environmental Dosimeter Batch Replacement," dated June 17, 1983. Particularly for audit dosimeters, the observed variability of field and audit results may be partially attributable to the reader system used and partially attributable to the calibration methodology used. The TLD reader system used a hot finger kept at constant temperature.

number of chips from three to five and to discard the high and low values. It is not known if this influx of new TLD-400 chips may have contributed to the observed increase in TLD dose rates. The switch over to the new chips was initiated in March 1984 after extensive testing of the replacement TLDs.

Table 3.3. Statistical Comparison of PNNL TLD Performance Data for 1985 Through 1990 and Coincident with the Sampling Periods for PNNL TLDs Co-Located with WDOH

			Performance Quotient (P_i)		Bias (%)	
Sample Group	TLD Sample Dates	Performance Audit Dates[a]	Mean[b] ±2SEM (n)	Scheffé's[b] ($P < 0.05$)	Mean[b] ±2SEM (n)	Scheffé's[b] ($P < 0.05$)
Moses Lake						
ML1	Jan 85–Oct 86	Feb 85–Jan 87	-0.016 ± 0.008 (143)	g	98.36 ± 0.732 (143)	j
ML2	Jan 87–Oct 88	Feb 87–Jan 89	-0.005 ± 0.012 (143)	g	99.48 ± 1.11 (143)	j
ML3	Jan 89–Oct 90	Feb 89–Dec 89	0.031 ± 0.018 (42)	h	103.11 ± 1.74 (42)	k
Connell						
Conn 1	Jan 85–Oct 86	Jan 85–Jun 86	-0.025 ± 0.008 (107)	q	97.52 ±0.748 (107)	x
Conn 2	Jan 87–Oct 88	Jul 86–Oct 88	-0.005 ± 0.010 (167)	r	99.47 ± 0.960 (167)	y
Conn 3	Jan 89–Oct 90	Nov 88–Dec 89	0.025 ± 0.016 (60)	s	102.46 ± 1.59 (60)	z

(a) Performance audit dates do not exactly match the TLD sample dates because of missing data for either the PNNL data sets and because PNNL sampling shifted from monthly to quarterly in mid-1989.
(b) Mean values (P_i or Bias) followed by the same letter are not significantly different for Scheffé's multiple comparison test ($P < 0.05$).
PNNL = Pacific Northwest National Laboratory.
SEM = Standard error of the mean.
TLD = Thermoluminescent dosimeter.

The developing bias in the TLD readings was recognized and steps were taken to address the issue even though the dose rates were low and considered background at many locations. These concerns led to the large increase in number of chips deployed in design 3 in 1990 as well as an expansion in the co-located deployment of TLDs with the WDOH.

The highly variable pattern observed from 1990 through 1994 (see Figure 3.5) corresponds to the period during which the 12-chip LiF dosimeter design was used (see Figure 3.4). In theory, dose calculations based on the average of 12 chip readings should have resulted in lower variability in reported results.

The chips were encapsulated in Teflon. This design has inherently less reproducible heating and is more prone to spurious signal from the Teflon and from contaminants on the Teflon or hot finger. Problems with the hot finger alignment and temperature control were noted often in the processing of personnel dosimeters during this time period. Inconsistent heating and spurious signal contributed to lower precision at low dose levels. The calibration method included calibration of the TLD chips but not

of the reader itself. No measurements or adjustments appear to have been made to compensate for drift in reader sensitivity between the field exposure readout and calibration exposure readout. An assumption of reader stability was inherent in the dosimeter calibration methodology. Any drift in reader gain or sensitivity could introduce error into the dosimeter calibration factor applied to field readings. It is thus possible that day-to-day changes in reader sensitivity may have contributed to the variability in field dosimeter results. It should be noted however, that the overall system bias for this TLD system based on audit dosimeter results from 1990 through 1994, was -0.028 (see Table 2.1). Therefore, it appears that, collectively, the dosimeter calibration was not significantly biased.

With the implementation of the Harshaw 8800 TLD reader and associated 8807 environmental dosimeter in 1995, the variability in readings decreased significantly and remained low over the subsequent 10 years. An important difference between systems is the readout methodology. The Harshaw 8807 system used a direct hot-gas stream instead of a direct hot finger as was used in the Hanford Personnel Multipurpose Dosimeter readers; this is a major factor in improving environmental dosimetry because of the improved signal-to-noise ratio. The new reader systems provided the capability for various pre-read, read, and anneal options that were used to improve the low-dose performance of the dosimeters.[1] In addition, the new dosimeters were packaged in a holder that had an O-ring seal and is more opaque than the previous system. The newer packaging provides protection from light, moisture, and dirt and may reduce the low-dose variability of the new system (Dirkes and Hanf 1996). The Hanford 12-chip TLD-700 dosimeters were not nearly as well protected from light, heat, moisture, and dirt as the newer 8807 TLDs.

With the transition from the 12-chip TLD-700 Hanford environmental dosimeter to the Harshaw 8807 dosimeter and 8800 TLD readers in 1995, there was also an apparent slight decrease in measured dose rates in the field. The observed drop in TLD readings is most likely due to differences in the fade characteristics of the two systems and small inaccuracies in the fade-correction factors applied. Unlike the cards from the 12-chip dosimeter, the cards from the 8807 dosimeter were not oven annealed for 30 minutes at 80°C before readout. Consequently, fading in the 8807 was slightly greater than in the Hanford 12-chip dosimeter (see Table 2.1). Because the two systems had similar dosimeter designs that used TLD-700 chips with only plastic filtration, they had similar energy-dependent responses. The apparent difference in field response between these two dosimeters is not likely due to differences in energy response. Measured dose rates in the field with the Harshaw 8807 system were still greater than with the early lead/tantalum-filtered capsule designs, as would be expected on the basis of the basic energy response curves for the CaF_2 and LiF dosimeter designs.

In summary, from the baseline established in the mid-1970s with the TLD-200 dosimeters, reported dose rates increased by about 40% between 1985 and 1995 with the three-chip TLD-400 and the 12-chip Hanford Personnel Multipurpose Dosimeter. The post-1995 Harshaw 8807 readings stabilized at dose rates similar to dose rates reported by the WDOH using TLD-100 LiF chips and at levels about 25% higher than the dose rates reported by PNNL from the mid-1970s through 1985. The observed trends in Hanford field data cannot be satisfactorily explained by the much smaller observed trends in blind audit dosimeter data. The most reasonable conclusion is that the apparent trend does not reflect an actual change in dose rates at Hanford, but rather a change in TLD materials, shielding, or laboratory practices during these years.

[1] Memo, from AW Endres to EJ Antonio, "Environmental TLD Co-Location Study," dated April 4, 1995.

Scatter-plot diagrams for locations used for environmental surveillance on the Hanford Site are provided in Appendices A (terrestrial locations) and B (shoreline locations). The general trends described for TLD performance and demonstrated with the Byer's Landing results also apply to these scatter plots.

3.3.3 Dose Rates by Location Grouping

The second fundamental question regarding the external radiation surveillance program to be addressed was whether there were differences in dose rates among the general regions where TLDs were deployed. Overall, external radiation levels at surveillance locations dropped following the decay of fallout activity in the 1970–1971 timeframe. These observations were also documented by WDOH background monitoring around the State of Washington (WDOH no date f, g). The mean dose rates stabilized around 0.18 to 0.21 mR/d at the perimeter, nearby and distant community location classes for the period from 1971 through 1989 (Table 3.4). The configuration of the 12-chip TLD-700 allows more of the lower-energy photons and possibly some high-energy beta particles to interact with the TLD crystals. These changes resulted in a slightly elevated mean dose rate ranging from 0.22 to 0.26 mR/d at the offsite location groupings of TLDs from 1990 through 1994. Because of the apparent greater variability in TLD response with the 12-chip TLD-700, the Harshaw TLD 8807 was deployed and during its deployment from 1995 through 2005, performed with greater consistency than previous TLD configurations. The mean dose rates for the offsite grouping ranged from 0.20 to 0.25 mR/d for the period of 1995 through 2005 with the Harshaw TLD-8807.

Table 3.4. Average Dose Rates (± Standard Deviation) by Distance Classification and Design and TLDs Submerged in the Columbia River

Distance Classification/ Location	TLD-200 1971–1976		TLD-400 1977–1989		TLD-700 1990–1994		8807 1995–2005	
	mR/d	Std. Dev	mR/d	Std. Dev	mR/d	Std. Dev	mR/d	Std. Dev
Onsite	0.25	0.18	0.25	0.46	0.32	0.84	0.24	0.02
Perimeter	0.21	0.04	0.20	0.03	0.26	0.05	0.25	0.02
Community								
Nearby	0.18	0.03	0.18	0.03	0.23	0.04	0.22	0.02
Distant	0.18	0.04	0.18	0.03	0.22	0.04	0.20	0.03
Shoreline	0.23	0.50	0.26	0.13	0.29	0.07	0.24	0.03
100-N Shore	0.14	0.06	0.60	0.25	0.64	0.28	0.34	0.12
Submerged	0.12	0.06	0.11	0.03	0.15[(a)]	0.04	NA	NA

(a) Columbia River submersion dose rate measurements were discontinued in mid-year 1992.
NA = Not available.
TLD = Thermoluminescent dosimeter.

Inspection of mean dose rates for the onsite, Columbia River shoreline, and 100-N Area shoreline groupings of TLDs indicates an influence of Hanford Site activities on dose rates. Some sites selected for TLD deployment were designed to monitor expected or existing increases in external dose rates. In these cases, the Hanford Environmental Surveillance TLD Program was complemented by the near-facility monitoring program. Because of the deployment site's closer proximity to actual sources in facilities and

waste sites, the near-facility monitoring program routinely measured greater dose rates than those recorded by the Hanford Environmental Surveillance TLD Program (e.g., Perkins et al. 2006).

Because of the direct discharge of cooling water to the Columbia River and the elevated presence of activation products in that cooling water, numerous surveys have been performed on the shoreline. In 1964 at the peak of single-pass reactor operation, shoreline dose for the avid fisherman were estimated as high 25 mrem/h as a result of the deposition of activation products along accessible portions of the Hanford Reach shoreline. Most of these activation products had very short half lives and by the time the TLD Environmental Surveillance program was initiated in 1971, nearly all of this activity had decayed away. Lodge (1966) provided a fairly comprehensive reactor area shoreline survey in 1966 and as a result of his findings, shoreline TLDs were deployed as the site deployed TLDs at upland sites in 1971–1972. In 1979, Sula (1980) conducted one of the more comprehensive surveys of river shoreline at Hanford. As a result of that survey and aerial surveys, the deployment of shoreline TLDs increased and was focused on the areas showing the highest levels of external radiation. Additional shoreline surveys were conducted in the 1990s (Cooper and Woodruff 1993).

Plutonium production involved a number of processes and facilities that may have contributed to external radiation on the Hanford Site (Table 3.5). Stapp (2002) provided an excellent overview of historic reactor operations at the Hanford Site, Conway and Freer (2002) provided an excellent overview of the historic Chemical Separations, and Gerber (2002) provided an overview of historic plutonium finishing. A detailed discussion of site operating practices in support of plutonium production is beyond the scope of this report. Major facilities and operating histories have been briefly summarized here to demonstrate activities that may have influenced measured dose rates on the site, either directly or by the management of waste derived from those activities.

The slightly elevated dose rates observed in the onsite grouping of TLDs, and most certainly specific locations in the 200 Areas and the 100-N Area shoreline TLDs, reflect the contribution from past plutonium production and waste management operations. The TLDs deployed around the perimeters of the 200-East and 200-West facilities (see Figure 3.1) most likely measured historic atmospheric deposition around these facilities from waste management and fuel processing activities that were taking place in the 200 Areas. In particular, TLDs located at 200-E East Central, 200-E North Central, and 200-E West Central detected elevated exposures that were indicative of radiological operations (Appendix A).

At the 100-N Area shoreline locations, the predominant source of elevated TLD readings can be attributed to skyshine from the liquid waste trenches. Skyshine is defined as scattered radiation of a primary gamma radiation source generated by aerial dispersion.

Additional detail about facility operating timeframes is summarized in Appendix C; however, readers seeking detailed information should review the references identified above.

The ANOVA conducted on the HEIS TLD data set indicated significant differences in variance estimates based on TLD type by distance classification (Table 3.6). Operationally, the data from 1985 to 1989 (five-chip replacement TLD-400) showed a distinct systematic increase in readouts over the duration of the deployment of the TLDs. The differences in mean response are not so apparent (Figure 3.6). The onsite TLDs have the greatest variability and this may be attributed to elevated readings from areas known to have higher-than-background exposure rates from site operations.

In a similar fashion, much greater variability was associated with TLD readings from the 100-N Area shoreline when compared to the other shoreline locations with the exception of the 1971 through 1976 period (Figure 3.7). At that time, N Reactor had only been operating since 1963 and the other single-pass reactors had recent operating history that contributed to elevated and variable shoreline readings. By 1976, much of the residual activity associated with shoreline locations at the single-pass reactor areas had decayed, bringing TLD readings into better alignment with background levels. In contrast, accumulations of radioactive liquid water in the trenches began to contribute to skyshine and were reflected in subsequent TLD measurements.

Table 3.5. Operating History of Hanford Site Plutonium Production Operations by Major Facility

Facility	Years Operated
Production Reactors	
KE	1955–1971
KW	1954–1970
N	1963–1987
Research Test Reactors	
HTR	1943–1971
TTR	1954–1978
PRCF	1962–1976
HTLTR	1968–1971
FFTF	1980–1994
Irradiated Fuel Reprocessing	
T	1944–1956, 1956–date[(a)]
PUREX	1956–1962, 1983–1988
UO_3	1956–1972, 1983–1991
225-B[(b)]	1968–1985
Reactor Fuel Fabrication	
313	1944–1971
314	1944–1971
333	1961–1987
303	1944–1987
306	1957–1984
Plutonium Finishing	
232-Z	1962–1973
2345-Z	1949–1989
236-Z	1964–1976
242-Z	1963–1976

(a) Used for decontamination after 1956.
(b) Cesium-137 and strontium-90 encapsulation.
FFTF = Fast Flux Test Facility
HTLTR = High Temperature Lattice Test Reactor.
HTR = Hanford Test Reactor.
PRCF = Plutonium Recycle Critical Facility.
PUREX = Plutonium-Uranium Extraction (facility).
TTR = Thermal Test Reactor.

Table 3.6. Summary of Analysis of Variance Analyses on TLD Type Within Each Distance Classification or River Shoreline Classification

Distance Classification	Calculated F	Critical F	P-Value
Onsite	8	2.61	<0.001
Perimeter	310	2.61	<0.001
Community	289	2.61	<0.001
Distant	41	2.61	<0.001
River Classification	Calculated F	Critical F	P-Value
Typical Shoreline	11	2.61	<0.001
100-N Shoreline	115	2.61	<0.001

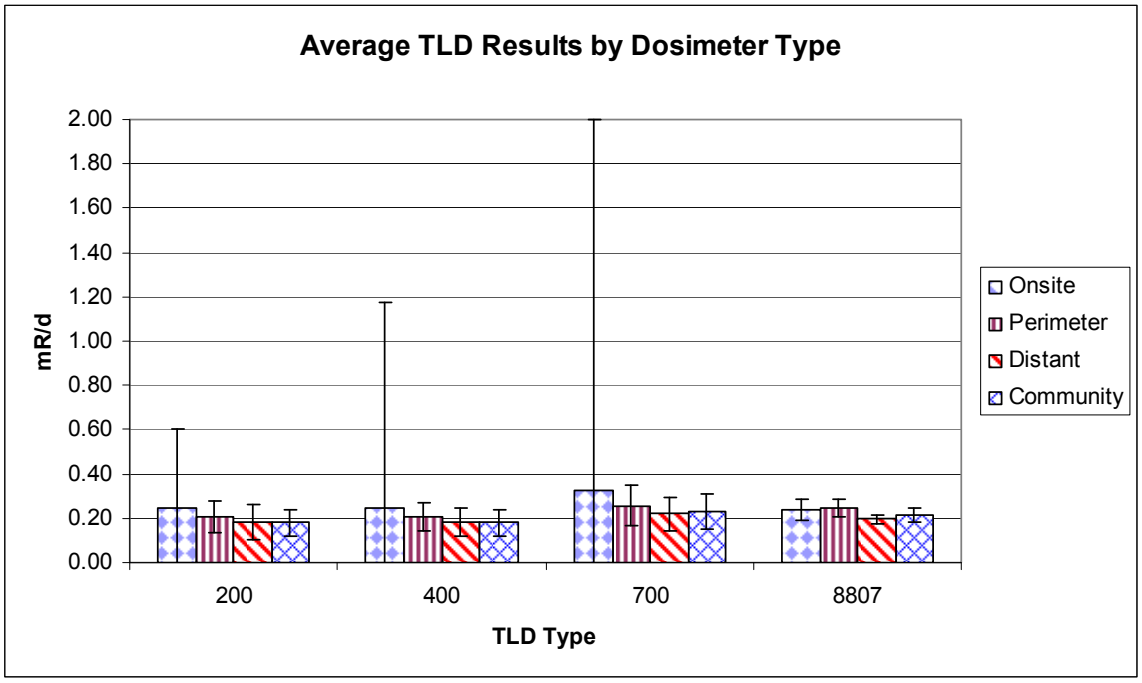

Figure 3.6. Mean TLD Results and 95 Percent Confidence Interval for Each Dosimeter Type Used at Hanford for Four Distance Classifications

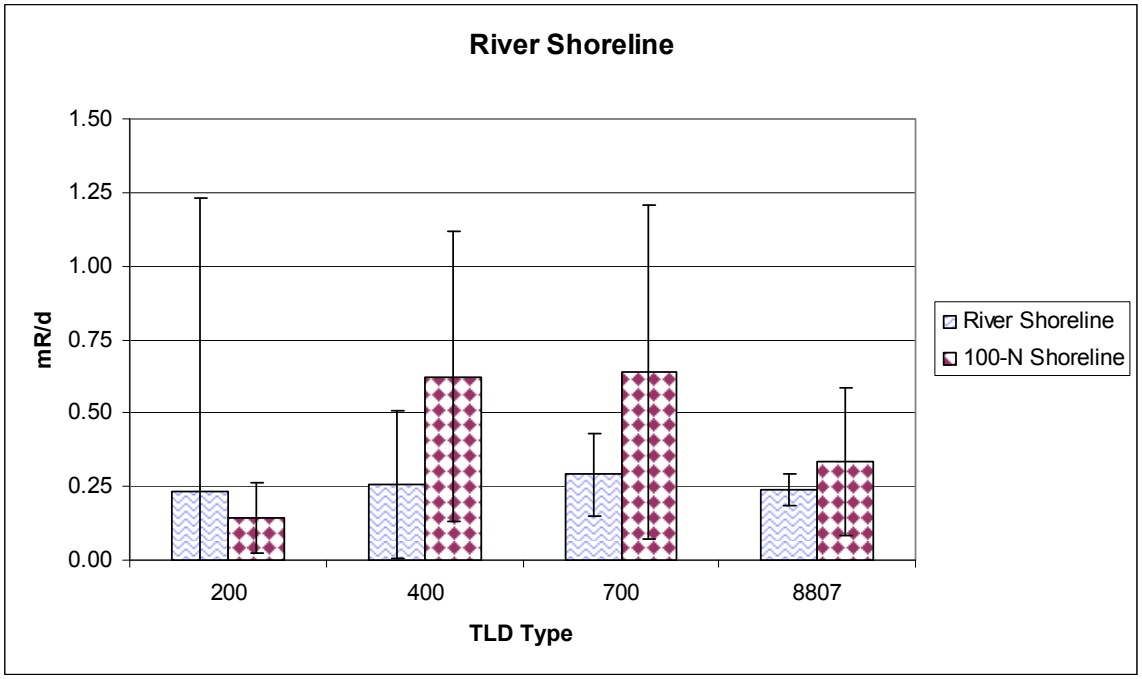

Figure 3.7. Mean TLD Results and 95 Percent Confidence Interval for Each Dosimeter Type Used at Hanford for the Typical River Shoreline and 100-N Shoreline Dosimeters

Surveillance TLDs also identified other activities that temporarily increased external dose rates onsite. In 1980 and 1981, elevated TLD readings were observed at the south end of the 300-A Trench, because a radioactive steam generator was temporarily stored near the trench. When shielding was removed from the generator in the latter half of 1981, dose rates increased at the 300-A Trench location. A new but temporary dosimeter location was established from February 1982 through September 1983 at the 377 Building to monitor continuing studies of the radioactive steam generator in the 300 Area.

Also, in 1983, a railroad tank car near the north side of the Fast Flux Test Facility (400 Area) caused elevated readings for months. The highest reading was 0.68 mR/d measured in October; the normal reading for the 400-N location was about 0.2 mR/d.

In 1993, a surveillance air sampler was moved downwind from its original location at the 100-N Washington Public Power Supply System location (steam generator building), to the edge of the 100-N 1325 Crib. The dosimeter that accompanied the air sampler was inadvertently moved. Public access to the 100-N 1325 Crib was not permitted and the TLD location was discontinued at the end of the third quarter. Dose rates along the 1325 Crib were about five to ten times higher than typical background levels.

These observations demonstrate the value of the surveillance network of TLDs in support of operations and the need to monitor potential sources of environmental and employee exposure. Other events that may have resulted in spurious readings are found in Appendix A and B with the scatter plots for each location.

4.0 Discussion

During their use from 1970 through 2005, TLDs were valuable tools for monitoring and evaluating environmental levels of gamma radiation, often times referred to as external or penetrating radiation in Hanford annual reports. The operating history tracks a progression of technological changes in configuration, chip composition, and reader systems that resulted in a large data base of environmental external radiation in the far field and offsite. There were operational issues as designs evolved, but the bias or potential for bias that may have occurred during these development phases did not overtly influence results. In fact, estimated dose rates even near areas of known radiation sources generally were well within the limits of natural variability in external radiation dose rates.

The TLD network complemented the air surveillance network and provided additional public assurance regarding potential radiation exposures from Hanford Site operations. With the termination of plutonium production at Hanford Site in 1990 and transition to a cleanup and restoration mission, the focus of site surveillance changed as waste streams were reduced and emissions decreased. Over time, resources for site surveillance were reduced, culminating with the discontinuation of the TLD program in 2005.

4.1 Termination of the Hanford Environmental Surveillance TLD Program

At the time that the surveillance TLD network was terminated in 2005, dose rates at most surveillance locations had stabilized to background levels of external radiation. Onsite locations where elevated readings were evident were associated with facilities or waste sites that were monitored by the existing near-field TLD program. A number of factors contributed to the decision to terminate the Hanford Environmental Surveillance TLD Program. The historic deployment of surveillance TLDs had provided a comprehensive database for external radiation and most of the stations that had at one time measured residual Hanford radiation essentially were measuring background radiation. The inventory of radionuclides in the environment had decreased due to radiological decay. Radionuclides like ^{60}Co, ^{152}Eu, ^{154}Eu, and ^{155}Eu simply were no longer measurable in soils or other environmental media. The primary contributor to external dose rates historically had been ^{137}Cs, and measurement of this fission product had decreased to or below detection levels in soil, water, vegetation, and wildlife samples in the far field and offsite.

A second and related consideration was that calculations of dose rates to members of the public to demonstrate compliance with regulatory standards were based on concentrations of specific radionuclides in liquid and gaseous effluents released from Hanford facilities. The predicted environmental concentrations were compared to measured radionuclide concentrations in those media and if the environmental measurements exceed the predicted environmental concentrations, the estimated dose rates were adjusted accordingly. At no time in recent years have the measured environmental concentrations been used to determine the maximally exposed individual dose rate. Dose rates associated with the TLD surveillance network were not used in this assessment process, but provided a confirmation and public assurance function rather than one for dose assessment. As such, the Hanford Environmental Surveillance TLD Program was judged by project management to provide less technical value than other surveillance tasks

(agricultural products, soil and vegetation, and wildlife) that produced mostly nondetectable radionuclide concentrations in environmental exposure media.

The decision to terminate the TLD program does not mean that the program was without merit. The program-derived data were a valuable component of the overall SESP and, particularly in the earlier years, identified areas of elevated radiation exposure, tracked changes in the environment, and provided a documented characterization of this aspect of the Hanford environment. Certainly, while the site was in plutonium production mode, the TLD network was a valuable asset for assessing and documenting site radiological conditions. It is unfortunate that the technology was not available during the 1950s and 1960s when plutonium production was ramping up and radiological releases to the environment were greater that what occurred after the shutdown of the single pass reactors between 1965 and 1971.

It is important to document the external radiological program for TLDs because it provides a source of environmental information that may be used for future site management decisions and as a reference for questions or issues relating to past operations and potential impacts from Hanford Site operations. After the TLD surveillance program was discontinued, the WDOH resurrected the shoreline portion of the program as part of its oversight activities. The WDOH's objectives are more focused on public assurance and validation of site monitoring programs rather than directly characterizing site conditions.

One subtle conclusion of this review is the realization that what is reported as a background dose rate is contingent upon a number of technical factors. Initial dose rates from the 1970s were lower in part because of shielding built into the TLD design. When shielding was changed to allow for interception of low-energy photons in 1985, dose rates were comparable to those with the shielding, but then increased through 1990 and into 1995 with the next change in design. Intuitively, with an increase to 12 total chips in design 3, sample variability would have been expected to decrease, but in fact over the next 5 years until the 8807 series was adopted, variability between deployments at all sites increased when compared to the variance associated with earlier TLD designs. The Harshaw 8807 has provided more precise and less variable results since 1995 and these are in agreement with TLD results published by the WDOH using LiF 100 Series chips (WDOH no date h).

Although there have been changes in reported dose rates over time, and these changes may be attributed to changes in TLD design and processing, the monitored incremental offsite dose rates that could have resulted from Hanford operations were a small fraction of background dose rates at most surveillance sites. Annual average dose rates to the public from ubiquitous background sources of exposure are about 310 mrem/yr (NCRP 2009), or essentially 0.85 mrem/d. Daily dose rates attributable to external radiation on the site ranged from 0.3 to 0.45 mR/d and occasionally up to 0.5 mR/d (1 mR $\approx$ 1 mrem). Exposure rates in excess of 0.5 mR/d were likely due to gamma radiation associated with residual activity related to site facilities or operations. Background dose rates conservatively could be approximated by measurements collected from areas distant from the central plateau on the site or at distant, offsite locations; these values ranged between 0.2 to 0.3 mR/d. Offsite dose rates attributable to external radiation were low and well within the range of normal and expected background dose rates.

Lastly, for special applications and situations, surveillance TLDs provided measurements onsite that monitored exposure rates where site workers could have inadvertently been exposed (e.g., the steam generator in the 300 Area). For the majority of site operations into the 1990s, public access to the site was restricted. Some current operations on the site (e.g., the Laser Interferometer Gravitational Wave Observatory, Energy Northwest, US Ecology) are non-federal activities and as such provide an

opportunity for members of the public to access portions of the site. The deployment of TLDs at these onsite areas proved assurance members of the public who work for private entities that their potential exposure to external sources of radiation at the Hanford Site was monitored.

Recently, the Hanford Site has been undergoing extensive cleanup and remediation. Present plans call for establishing an area of approximately 75 square miles on the Central plateau that will be dedicated to the long term storage and environmentally safe management of Hanford's remaining nuclear waste. Some environmental surveillance will be necessary to document the efficacy of institutional and engineering controls for managing this waste. Advances in radiation detection technology will likely provide more timely and accurate surveillance tools that exceed the sensitivity and functionally of thermolunminescent dosimetry. During the 35 years of the Environmental Surveillance TLD program at Hanford, this network provided meaningful and useful data on the state of the Hanford Site and adjoining properties and served to verify that modeled dose rates to the public were in agreement with dose rates derived from this technology.

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Appendix A

TLD Graphical Data Summaries by Sample Location for Upland Terrestrial Locations on and off the Hanford Site

Appendix A

TLD Graphical Data Summaries for Upland Terrestrial Locations on and off the Hanford Site

This appendix contains graphs of upland thermoluminescent dosimeter (TLD) results derived from data in the Hanford Environmental Information System (HEIS) from January 1971 through December 2005. Some of these graphs distinguish between TLD designs; however, none of them specify duration of deployment (biweekly, monthly, or quarterly). At some locations, dosimeters of different designs were co-deployed to meet different objectives. Over the 35-year duration of the Hanford Environmental Surveillance TLD Program, the actual placement of a dosimeter at some locations may have changed slightly. Different names may have been used to identify the same location. This appendix documents these changes for each location and presents the trends in external radiation measurements over the duration of TLD deployment.

When TLDs were first deployed in 1970, the surveillance design consisted of onsite, shoreline, southeast quadrant, and perimeter regions. Some perimeter locations were more distant than sites that are now categorized as perimeter and in the more recent scheme would have been designated as community sampling stations. Generally, TLDs were deployed at upland locations in conjunction with ambient air sampling stations. Deployment regions for offsite TLDs were categorized as perimeter, nearby community, and distant community and are discussed later in this appendix. Data from onsite locations were organized by operating areas (e.g., 100 Areas, 200 Areas).

TLD locations that were operational in the late 1990s through the time when the surveillance program was terminated in 2005 had been established using global positioning system (GPS) technology and coordinates were obtained at the TLD sampling locations. For retired locations, the GPS coordinates were approximated using Google Earth (Google, Inc. 2009) based on maps in annual environmental reports, descriptions of locations in the locations manual,[1] historic internal versions of location manuals, and project files. For some of the older locations where TLDs were deployed for only a short time (e.g., barges on the river), TLD coordinates could not be re-established. All GPS coordinates for these early locations are best estimates based on historic records.

The upland sites are complemented by a network of Columbia River shoreline locations (see Appendix B).

A.1 General Observations

At many locations, fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in a slight but abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973). These increases were generally not evident at locations with elevated external dose rates attributable to site operations.

[1] Pacific Northwest Laboratories (PNL). 1983. *Environmental Sampling Locations Manual*, Battelle-Pacific Northwest Laboratories, PNL-MA-514, Richland, Washington (internal manual).

At other times, elevated readings are apparent in the scatter plots and the site reports and HEIS comment fields were reviewed to determine if there was an explanation for such elevated readings.

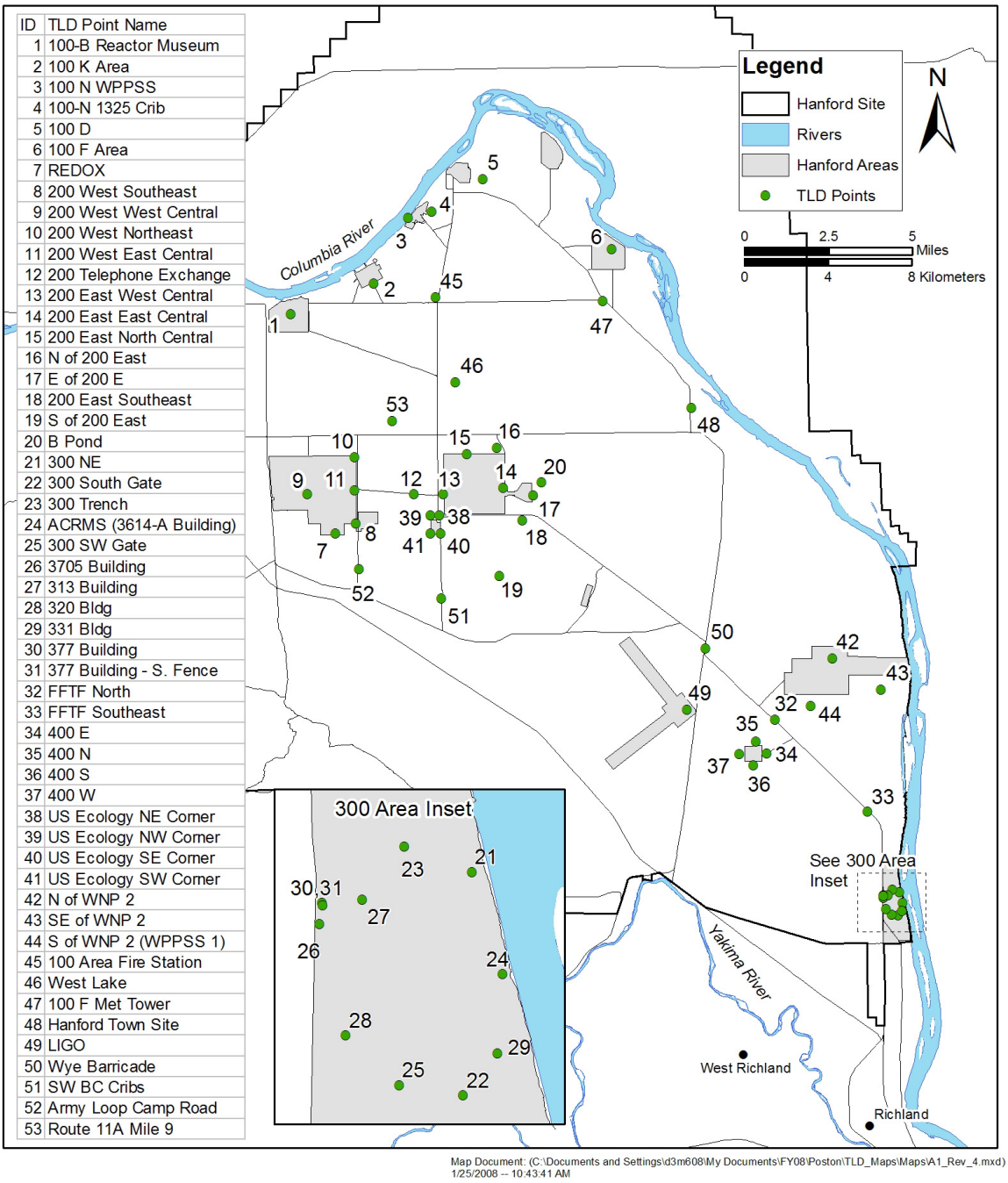
In the 1970s, some TLD values were entered into HEIS as zero values. These may be TLDs that were lost or failed during analysis and the laboratory simply inserted a "0." These values were included in the scatter plots but should not be interpreted to mean that no dose was measured.

For those sites that were active in 2005 when surveillance TLD sampling was terminated, samples were collected up through December of 2005. Many of the charts, as formatted, show December 2004 as the last displayed date on the figures abscissa, even though data are shown beyond this date through 2005. This is a formatting problem of the computer software and there has been no attempt to reformat the figures to show December 2005 on the abscissa.

All figures contain a title above the figure that displays the name of the site as it appears in the HEIS database. The HEIS software is configured in a way that limits the number of characters that can be used to name a sampling location. In some cases, portions of words or abbreviations have been truncated to accommodate HEIS format specifications and they are produced in the figure field as they appear in HEIS.

A.2 Upland TLD Sampling Locations on the Hanford Site

A total of 53 TLD sampling sites were established on the Hanford Site during the course of the 35-year operating history of the Hanford Environmental Surveillance TLD Program (Figure A.1). Some stations were sampled for less than a year while others were sampled for the entire duration of the TLD campaign (Table A.1).



ID	TLD Point Name
1	100-B Reactor Museum
2	100 K Area
3	100 N WPPSS
4	100-N 1325 Crib
5	100 D
6	100 F Area
7	REDOX
8	200 West Southeast
9	200 West West Central
10	200 West Northeast
11	200 West East Central
12	200 Telephone Exchange
13	200 East West Central
14	200 East East Central
15	200 East North Central
16	N of 200 East
17	E of 200 E
18	200 East Southeast
19	S of 200 East
20	B Pond
21	300 NE
22	300 South Gate
23	300 Trench
24	ACRMS (3614-A Building)
25	300 SW Gate
26	3705 Building
27	313 Building
28	320 Bldg
29	331 Bldg
30	377 Building
31	377 Building - S. Fence
32	FFTF North
33	FFTF Southeast
34	400 E
35	400 N
36	400 S
37	400 W
38	US Ecology NE Corner
39	US Ecology NW Corner
40	US Ecology SE Corner
41	US Ecology SW Corner
42	N of WNP 2
43	SE of WNP 2
44	S of WNP 2 (WPPSS 1)
45	100 Area Fire Station
46	West Lake
47	100 F Met Tower
48	Hanford Town Site
49	LIGO
50	Wye Barricade
51	SW BC Cribs
52	Army Loop Camp Road
53	Route 11A Mile 9

Figure A.1. Upland TLD Sampling Locations on the Hanford Site (Figures A.2–A.53)

Table A.1. Global Positioning Coordinates and Years of Data Collection at Onsite Upland TLD Sampling Locations

Name	Latitude	Longitude	Sampling Period (Years)	Page
100 Areas				
100-B Reactor Museum	46.63100	-119.64778	2001–2005	A.6
100-K Area	46.643988	-119.59572	1971–2005	A.6
100-N WPPSS	46.672658	-119.573661	1971–1995	A.7
100-N 1325 Crib	46.675369	-119.5588072	1992	A.7
100-D Area	46.689479	-119.526817	1971–2005	A.8
100-F Area	46.65788	-119.446382	1971–1977	A.8
Central Plateau				
REDOX	46.534159	-119.621354	1971–1982	A.9
200-West Southeast	46.538616	-119.608723	1988–2005	A.9
200-West West Central	46.551698	-119.638873	1971–1982	A.10
200-West Northeast	46.567784	-119.609023	1971–1982	A.10
200-West East Central	46.553255	-119.609167	1971–1982	A.11
200 Telephone Exchange	46.551265	-119.572352	1983–2005	A.11
200-East West Central	46.551008	-119.553779	1971–1982	A.12
200-East East Central	46.553599	-119.516487	1971–1982	A.12
200-East North Central	46.568542	-119.538943	1971–1982	A.13
N of 200-East	46.571171	-119.519971	1983–2005	A.13
E of 200-E	46.550166	-119.497579	1983–2005	A.14
200-East Southeast	46.53908	-119.504666	1971–2005	A.14
S of 200-East	46.514645	-119.519424	1983–2005	A.15
B Pond	46.555769	-119.492259	1988–2005	A.15
300-400 Area				
300 NE	46.373175	-119.273003	1989–2005	A.16
300 South Gate	46.36297	-119.273791	1972–2005	A.16
300 Trench	46.374382	-119.277357	1971–2005	A.17
ACRMS (3614-A Building)	46.368538	-119.271093	1971–1989	A.17
300 Water Intake			1989–2005	
300 SW Gate	46.43501	-119.357245	1972–2005	A.18
3705 Building	46.370905	-119.282907	1971–2005	A.18
313 Building	46.365825	-119.281578	2000–2005	A.19
320 Bldg	46.365788	-119.281334	1971–1972	A.18
331 Bldg	NA	NA	1971–1976	A.19
377 Building	NA	NA	1981–1983	A.20
377 Building, S. Fence	46.370563	-119.282825	1983–1988	A.20
FFTF North	46.450007	-119.348554	1973–1990	A.21
FFTF Southeast	46.40895	-119.292001	1973–1990	A.21

Table A.1. (contd)

Name	Latitude	Longitude	Sampling Period (Years)	Page
400 E	46.439072	-119.363928	1971–2005	A.22
400 N	46.429568	-119.359207	1979–2005	A.22
400 S	46.43498	-119.368594	1979–2005	A.23
400 W	46.36297	-119.273791	1979–2005	A.23
WDOH Co-located TLDs				
US Ecology NE Corner	46.54175	-119.55622	1985–2005	A.24
US Ecology NW Corner	46.54186	-119.561865	1985–2005	A.24
US Ecology SE Corner	46.533787	-119.555785	1985–2005	A.25
US Ecology SW Corner	46.533693	-119.561981	1985–2005	A.25
N of WNP 2	46.47643	-119.31250	1985–1988	A.26
SE of WNP 2	46.46250	-119.28250	1985–1988	A.26
S of WNP 2 (WPPSS 1)	46.416885	-119.237452	1985–2005	A.27
600 Area				
100-Area Fire Station	46.637602	-119.557285	1972–1990	A.28
West Lake	46.600363	-119.545244	2001-2005	A.28
100-F Met Tower	46.635038	-119.452439	1998–2005	A.29
Hanford Townsite	46.587641	-119.397979	1985–2005	A.29
LIGO	46.454865	-119.403412	2002–2005	A.30
Wye Barricade	46.481704	-119.39146	1971–1995; 1997–2005	A.30
SW BC Cribs	46.505206	-119.555754	1983–1992; 2000–2005	A.31
Army Loop Camp	46.518475	-119.60698	1982–1990; 1998–2005	A.31
Route 11, Mile 9	46.578049	-119.591602	1985–1989	A.32

ACRMS = Automatic Columbia River Monitoring Station.
FFTF = Fast Flux Test Facility.
LIGO = Laser Interferometer Gravitational Wave Observatory.
REDOX = Reduction-Oxidation (Plant).
TLD = Thermoluminescent dosimeter.
WDOH = Washington State Department of Health.
WPPSS = Washington Public Power Supply System.
WNP = Washington Nuclear Plant.

A.2.1 TLD Results at 100 Area Locations

This section contains plots of TLD data for upland TLD sampling locations for the 100 Areas on the Hanford Site (Figures A.2 through A.7).

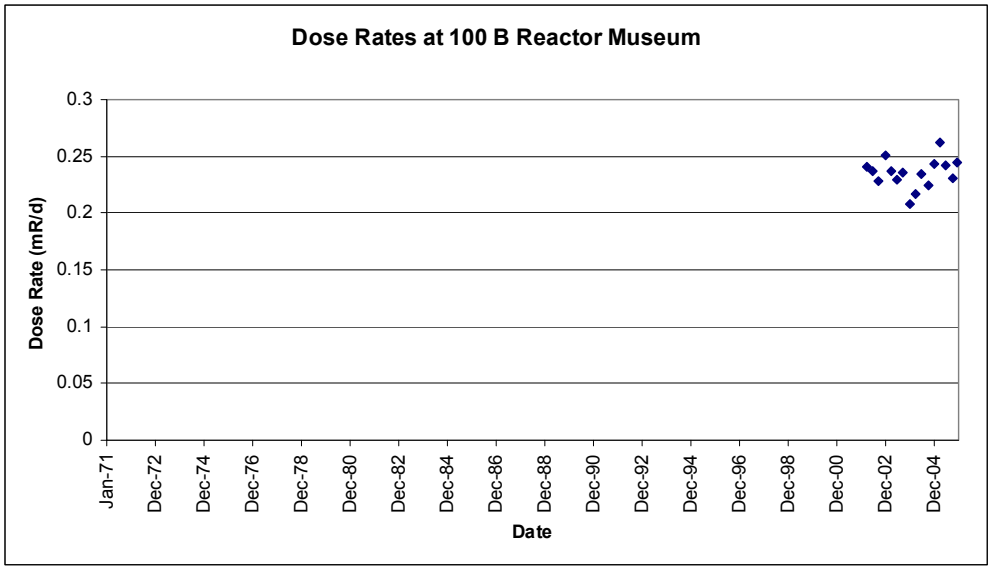


Figure A.2. Dose Rates Were Measured Quarterly at 100-B Reactor Museum Beginning in the First Quarter of 2002 Through December 2005. The dosimeter was located on the west side of B Reactor (105-B Building) along the exclusion fence.

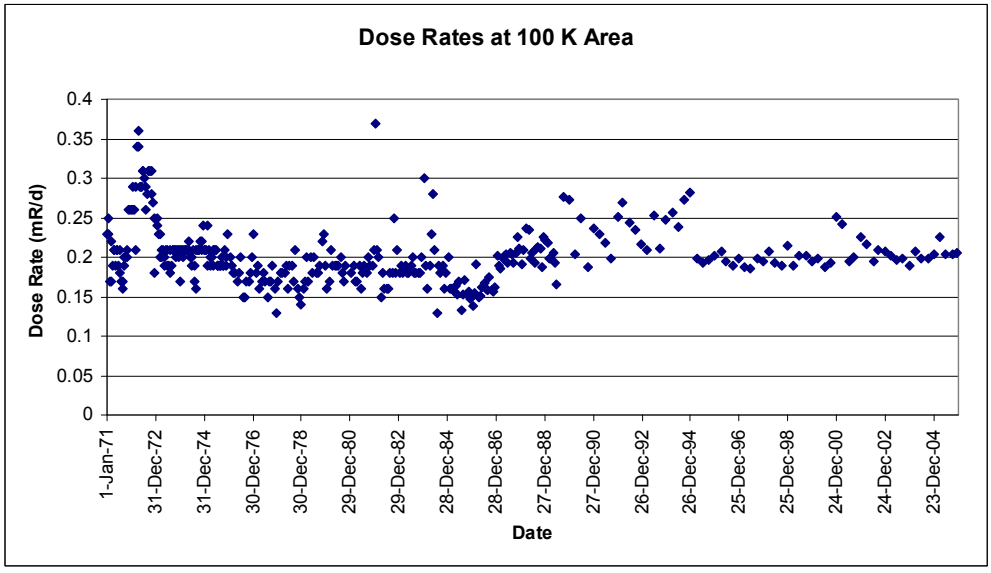


Figure A.3. Dose Rates Were Measured in the 100-K Area from January 1971 through December 2005. The dosimeter was located on the east side of the road, approximately halfway between the railroad tracks and the 100-K main gate. No comments found regarding high dose rates observed in 1972 at the 100-K Area TLD location. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

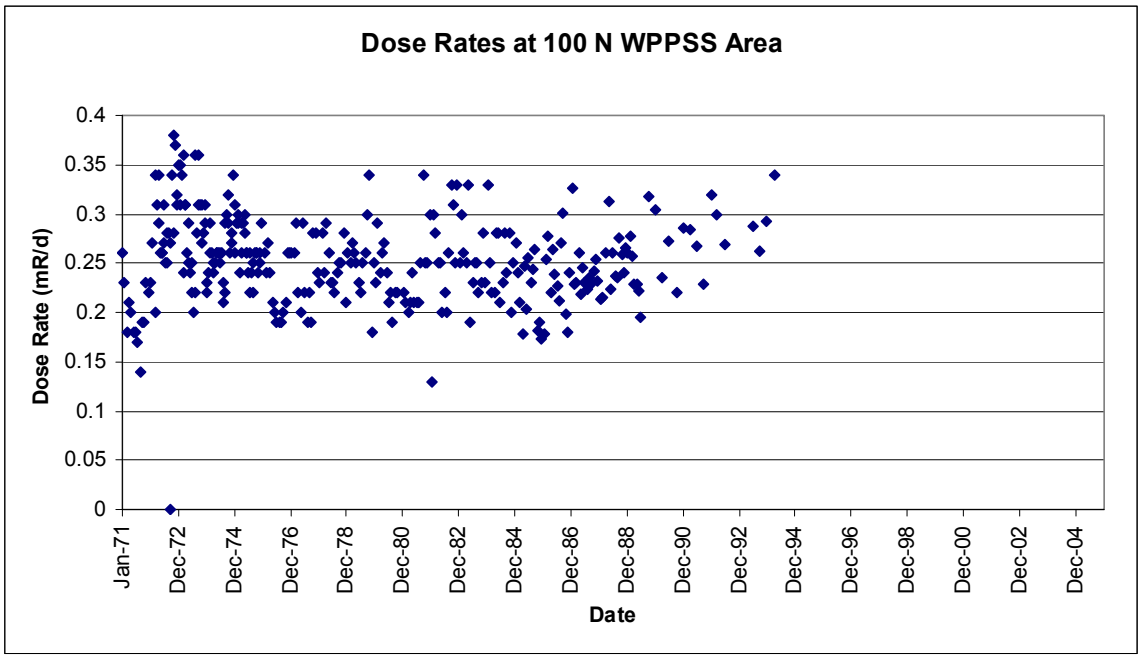


Figure A.4. Dose Rates Were Measured at the 100-N Washington Public Power Supply System (WPPSS) Location from January 1971 Through March 1994. The dosimeter was located on the fence around the steam-generating plant, on the bank of the Columbia River. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

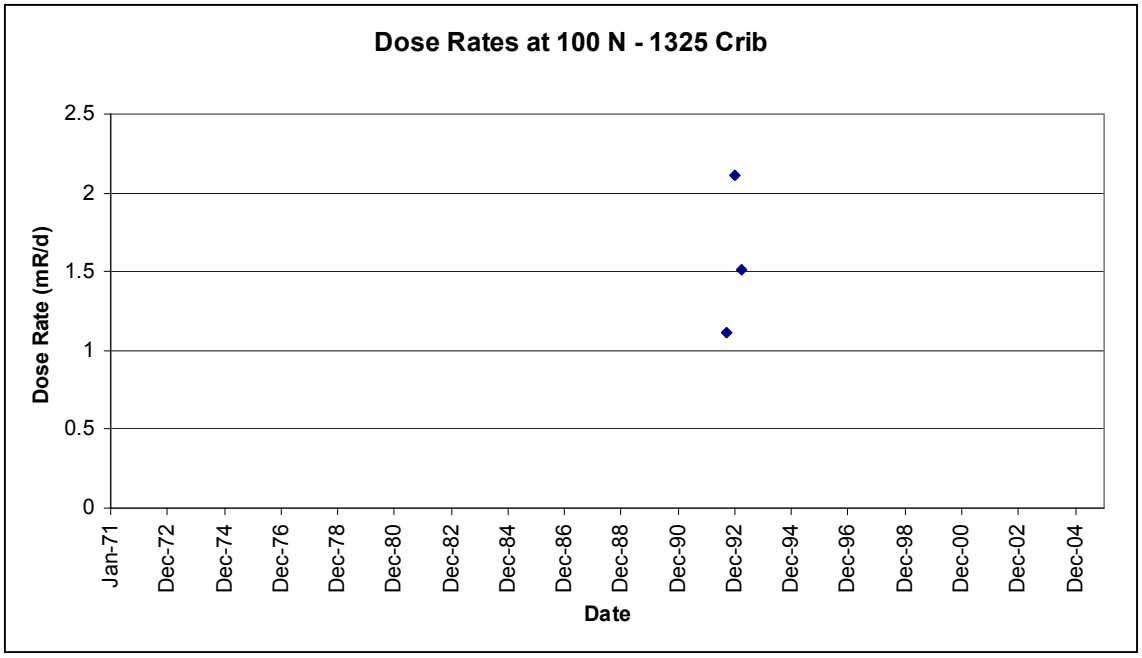


Figure A.5. No Comments Were Found Regarding Dose Rates Measured at the 100-N 1325 Crib Area TLD Location. This location was inadvertently moved from 100-N WPPSS to the edge of the 1325-N Crib with a co-located air sampler and discontinued because the crib was the responsibility of the Near-Field Program.

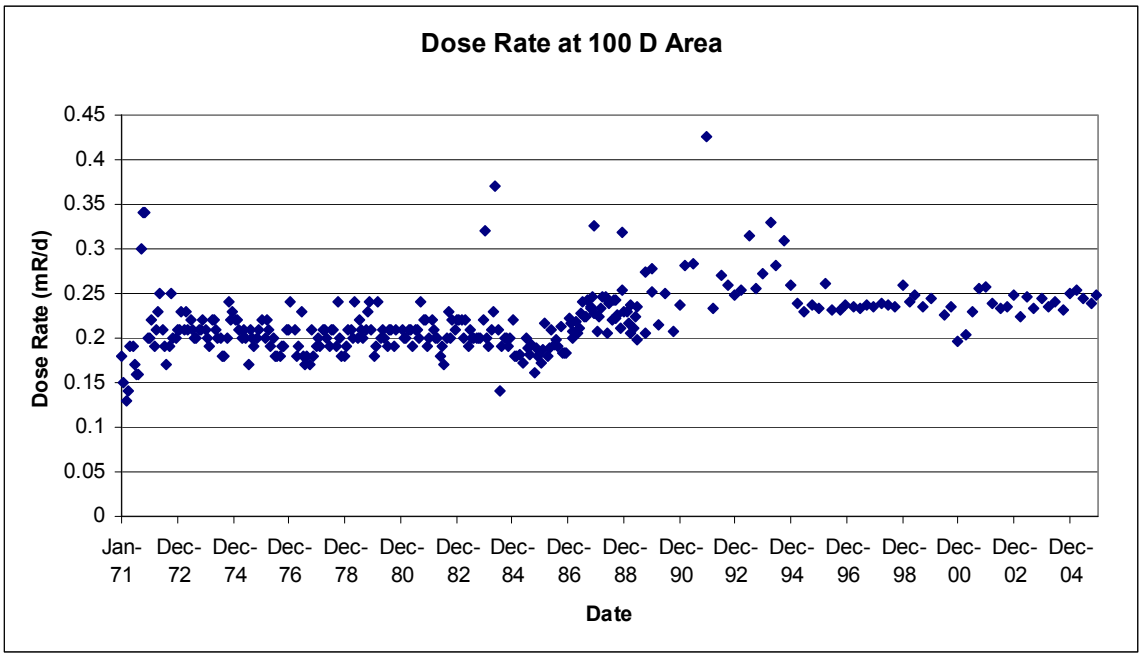


Figure A.6. Dose Rates Were Measured in the 100-D Area from January 1971 Through December 2005. The dosimeter was located approximately 0.3 mile north of Route 2 North along the road leading to the east entrance to the 100-D Area. No discussion was found regarding highest observed reading at 100-D Area TLD location for third quarter of 1991 and no comments were in the HEIS database.

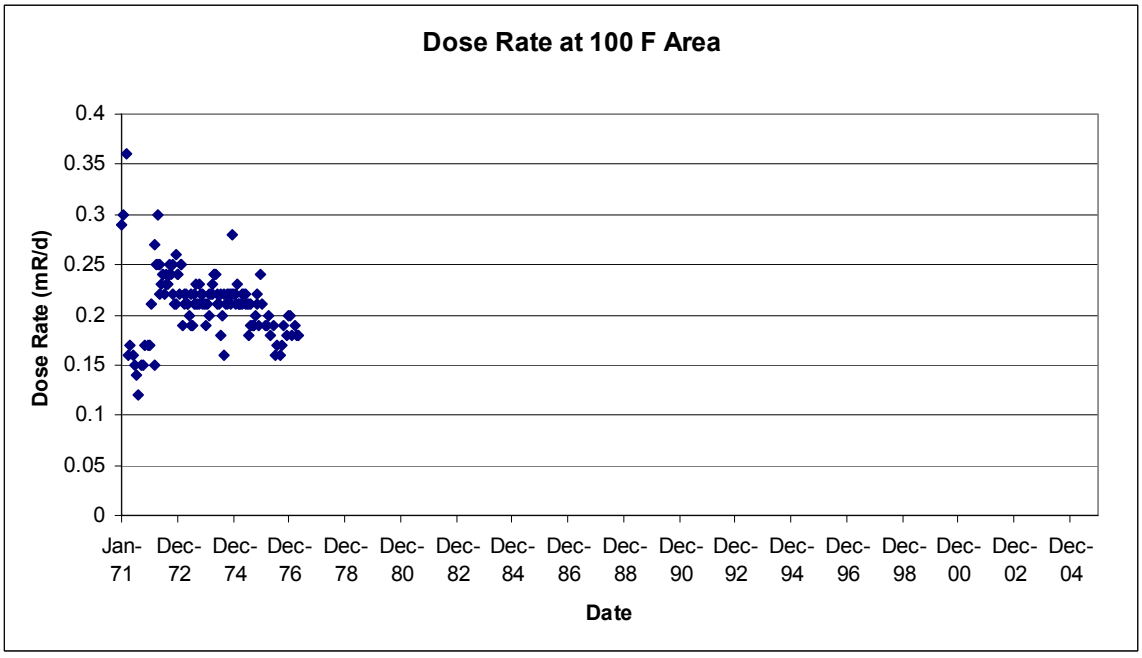


Figure A.7. Dose Rates Were Measured in the 100-F Area from January 1971 Through May 1977. No comments were found in annual reports regarding highest dose rate observed at the 100-F Area TLD location. The first 3 months of TLD deployment at this location were the highest in its history and were associated with fallout from foreign weapons testing (Bramson and Corley 1973). Dose rates decreased to about half the 1971 rates by 1976.

A.2.2 TLD Results at Central Plateau (200 Areas) Locations

This section contains plots of TLD data for upland TLD sampling locations for the Central Plateau on the Hanford Site (Figures A.8 through A.21).

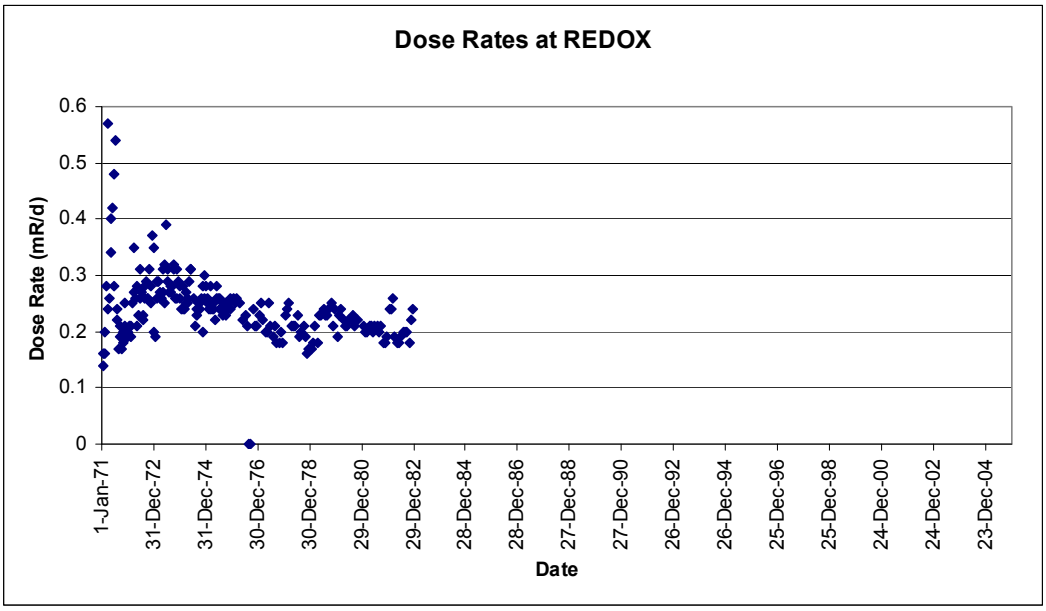


Figure A.8. Dose Rates Were Measured at the Reduction-Oxidation (REDOX) Plant from January 1971 Through December 1982. The REDOX facility reprocessed uranium fuel from 1952 through 1967 and reprocessed almost 25,000 tons of fuel during its operation. The elevated observations in 1971 were likely related to facility operations.

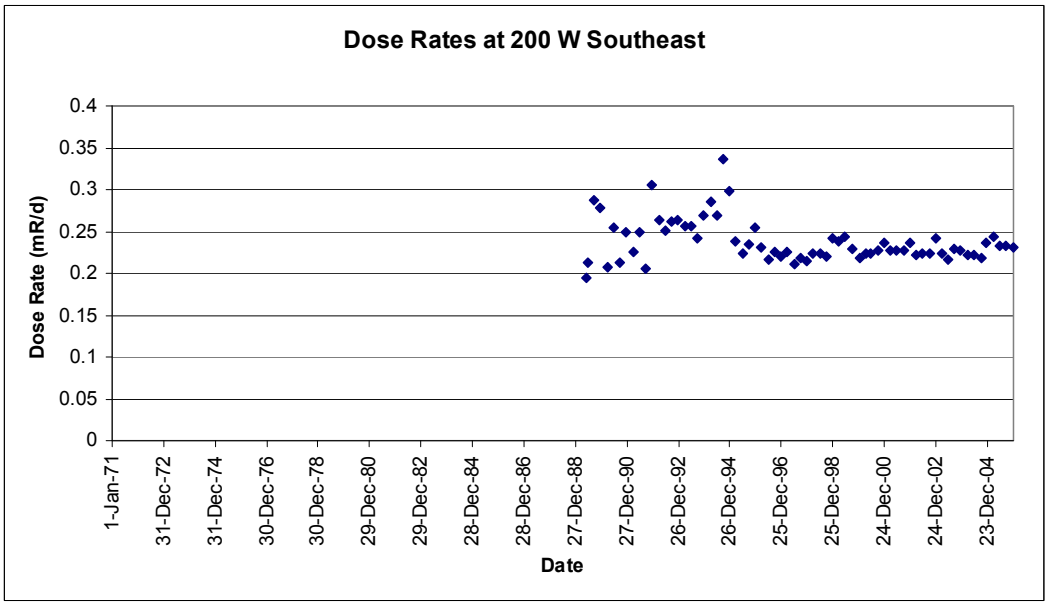


Figure A.9. Dose rates were measured at 200-W Southeast from May 1989 through December 2005. The dosimeter was located along the perimeter fence near the corner of Albany and 13th Streets.

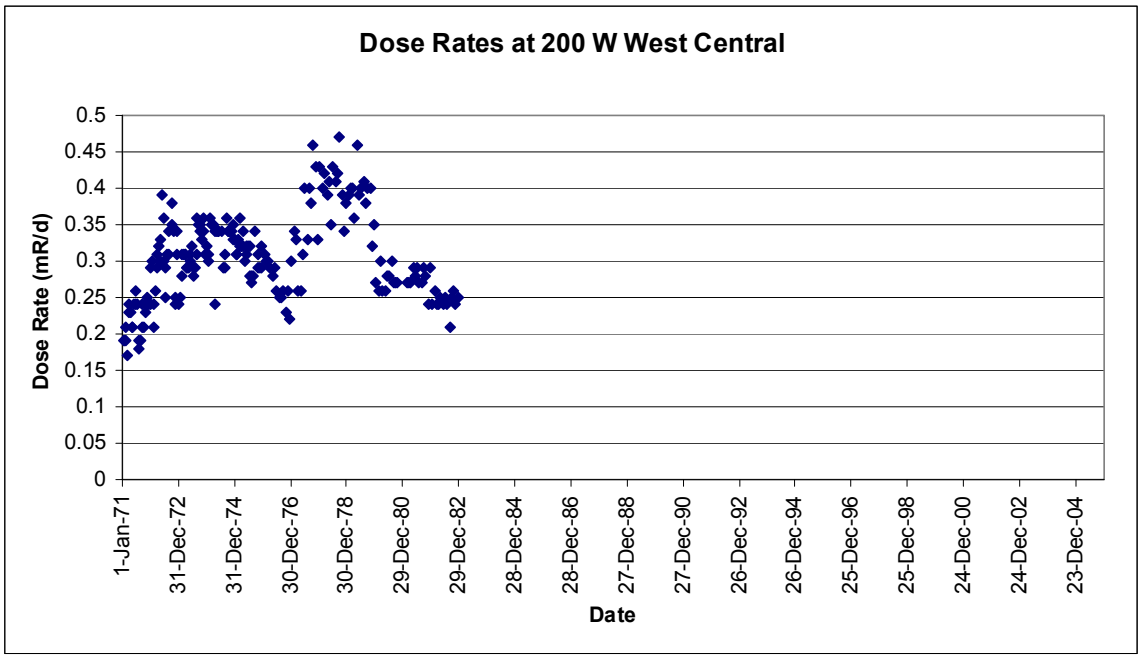


Figure A.10. Dose Rates Were Measured at 200-W West Central from January 1971 Through December 1982. This dosimeter was located on the perimeter fence near the intersection of Dayton Avenue and 19th Street. Dose rates may have been influenced by waste management activities.

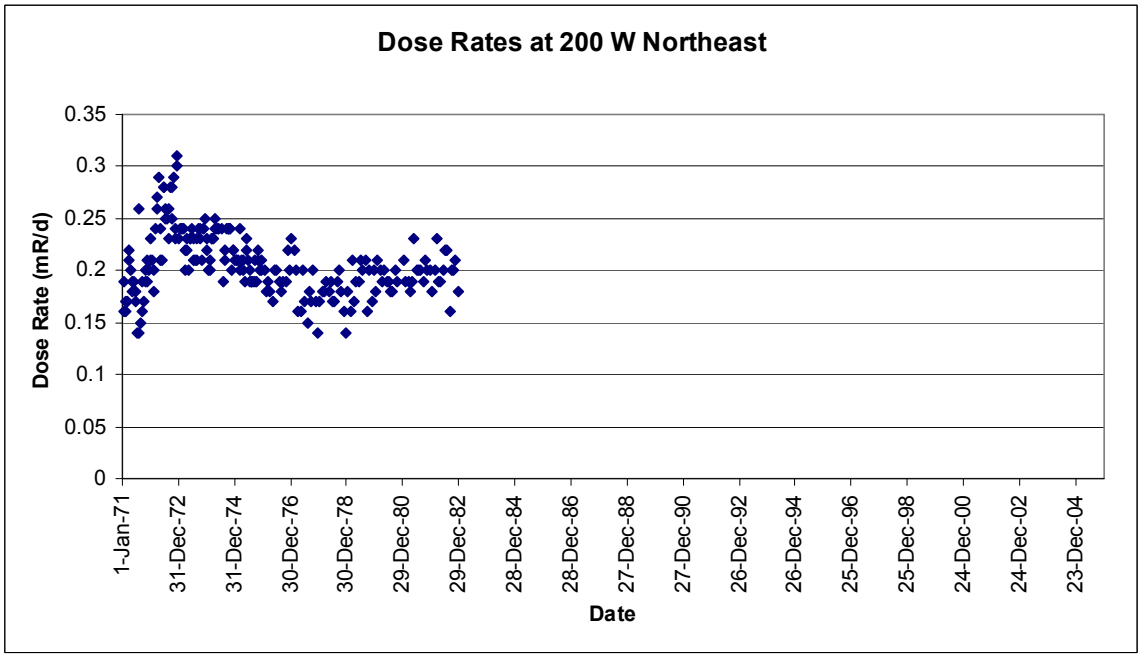


Figure A.11. Dose Rates Were Measured at 200-W Northeast from January 1971 Through December 1982. This dosimeter was located along the perimeter fence in the northeast corner of the 200-West Area.

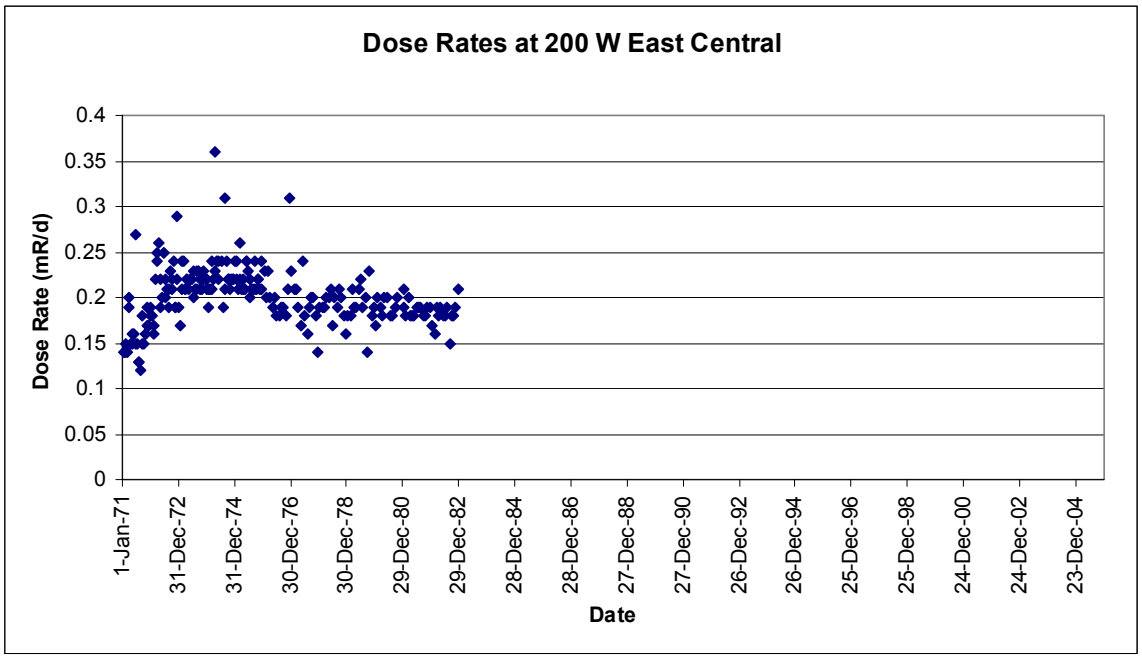


Figure A.12. Dose Rates Were Measured at 200-W East Central from January 1971 Through December 1982. This dosimeter was located on the perimeter fence just south of the east gate of the 200-West Area.

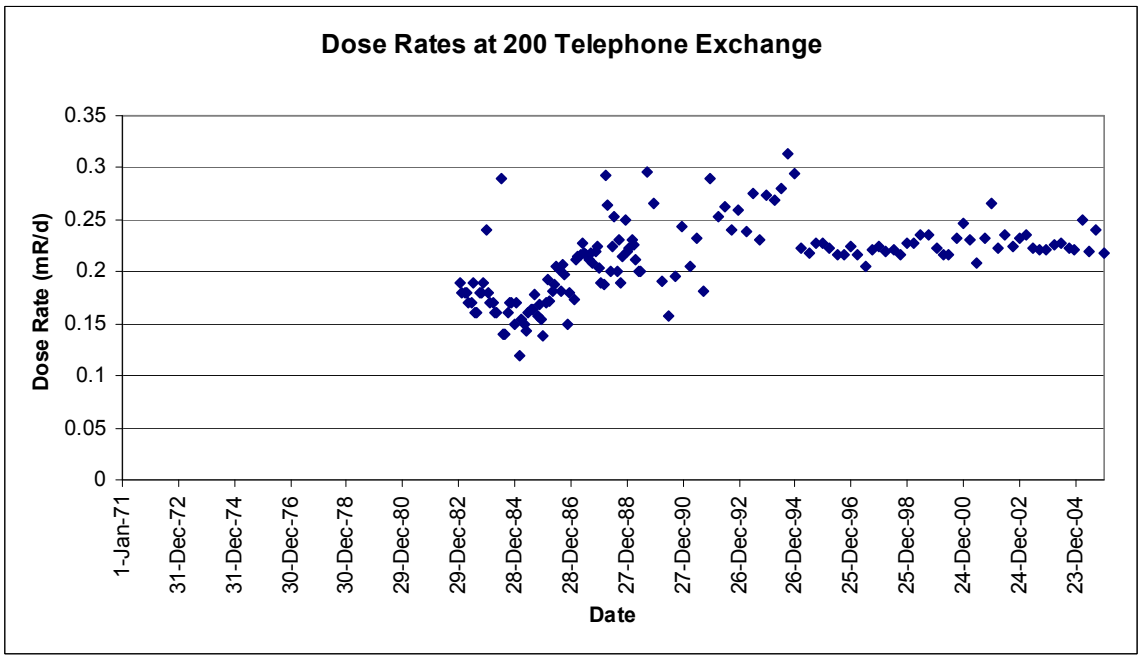


Figure A.13. Dose rates were measured at 200 Area Telephone Exchange from January 1983 through December 2005. The dosimeter was located on Route 3 between the 200-East Area and 200-West Area, about 0.5 mile from the intersection of Route 3 and Route 4S.

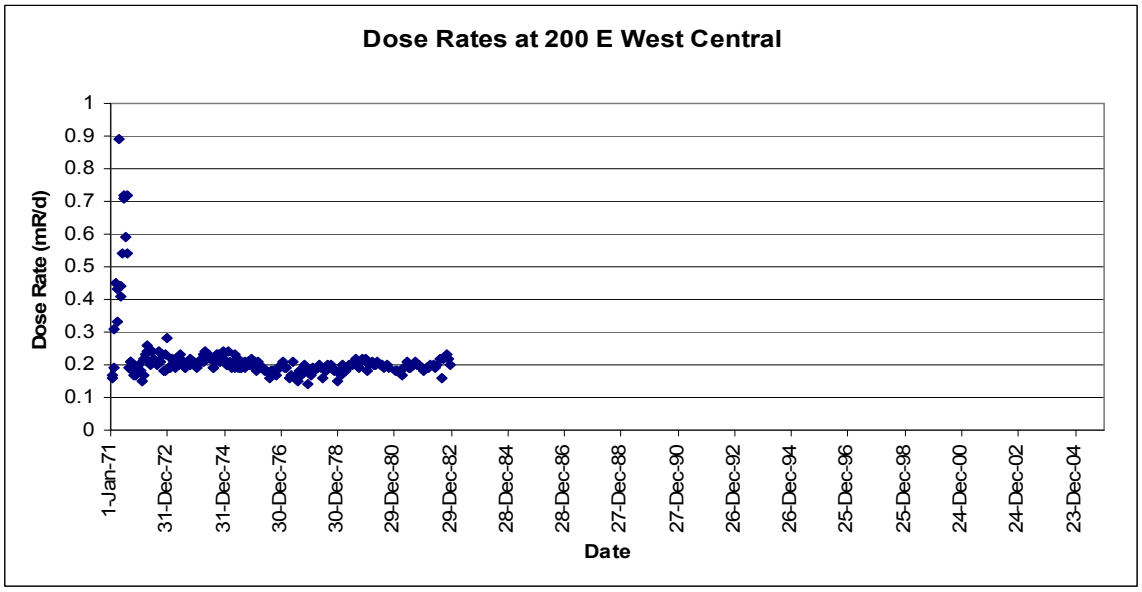


Figure A.14. Dose Rates Were Measured at 200-E West Central from January 1971 Through December 1982. The dosimeter was located on the perimeter fence of the 200-East Area, near the intersection of Akron Ave and 4th Street (PNL-MA-514[1]). Dose rates in 1971 were much higher than the fallout spike noted at other locations.

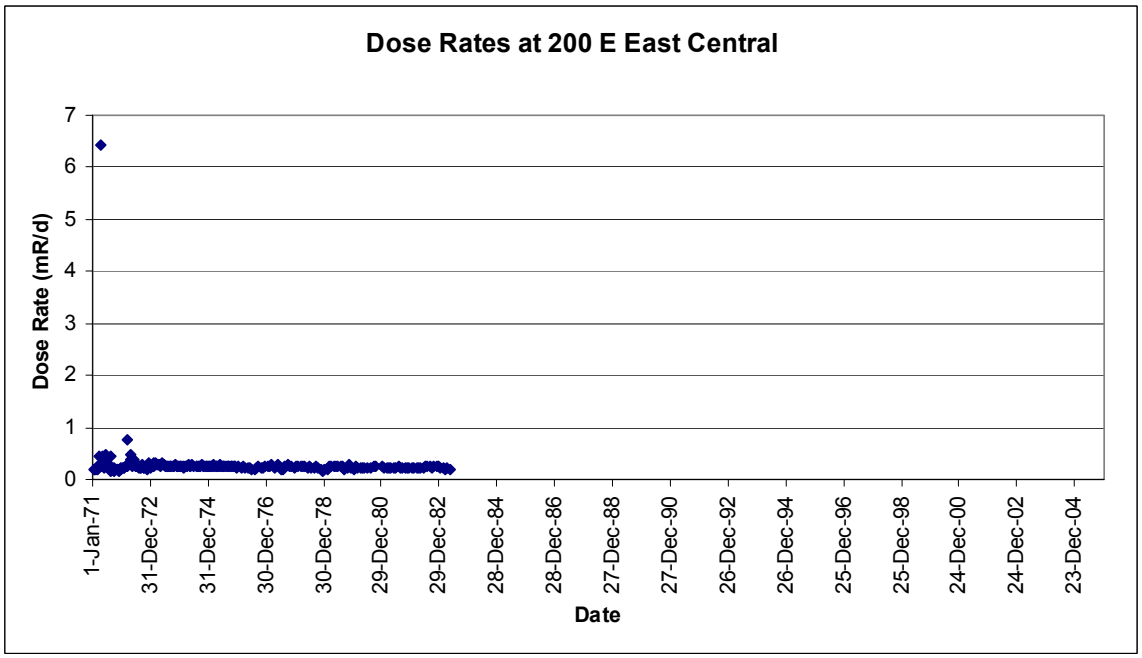


Figure A.15. Dose Rates Were Measured at 200-E East Central (200 EEC) from January 1971 Through May 1983. The 200 EEC location was on Canton Avenue approximately halfway along the inside of the 200-East perimeter fence. During 1971, 200 EEC was the onsite location with the maximum 6-month average exposure rate for any onsite location, 0.8 mR/d, compared with 0.17 for a number of offsite locations (Bramson and Corley 1973).

[1] Pacific Northwest Laboratories (PNL). 1983. *Environmental Sampling Locations Manual*, Battelle-Pacific Northwest Laboratories, PNL-MA-514, Richland, Washington (internal manual).

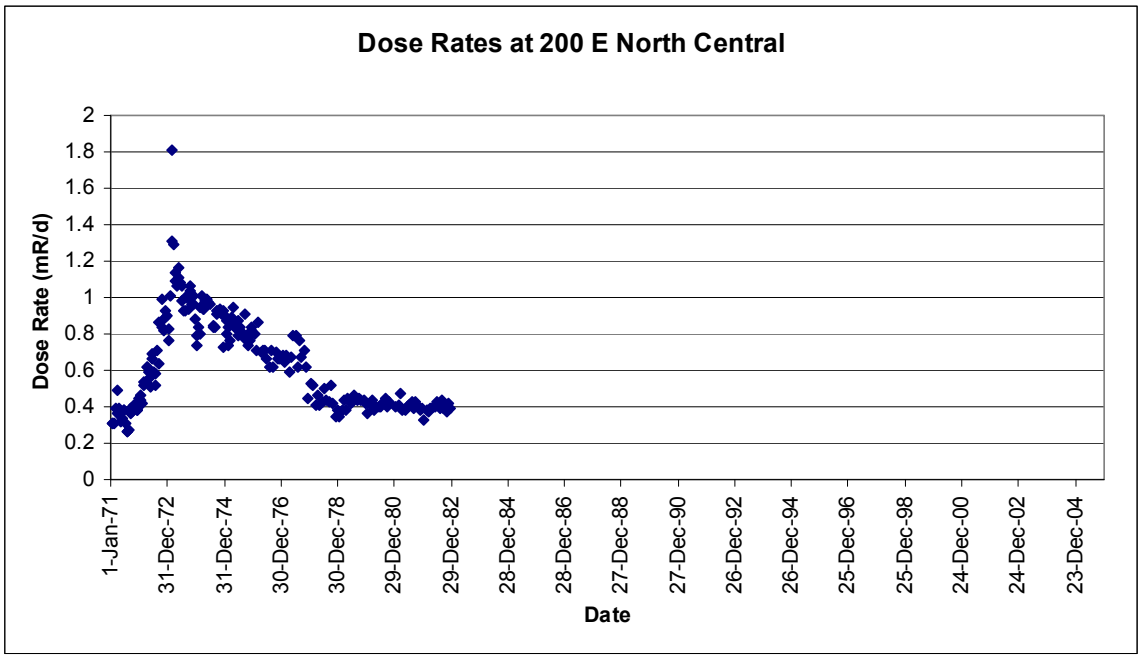


Figure A.16. Dose Rates Were Measured at 200-E North Central (200 ENC) from January 1971 Through December 1982. The 200 ENC dosimeter was located on the perimeter fence near the intersection of Baltimore Avenue and 12th Street. Dose rates may have been influenced by waste management activities of the B Complex. The average 6-month exposure rate at 200 ENC was around 1.2 mR/d for 1973 compared with 0.19 mR/d at a number of offsite locations (Nees and Corley 1973).

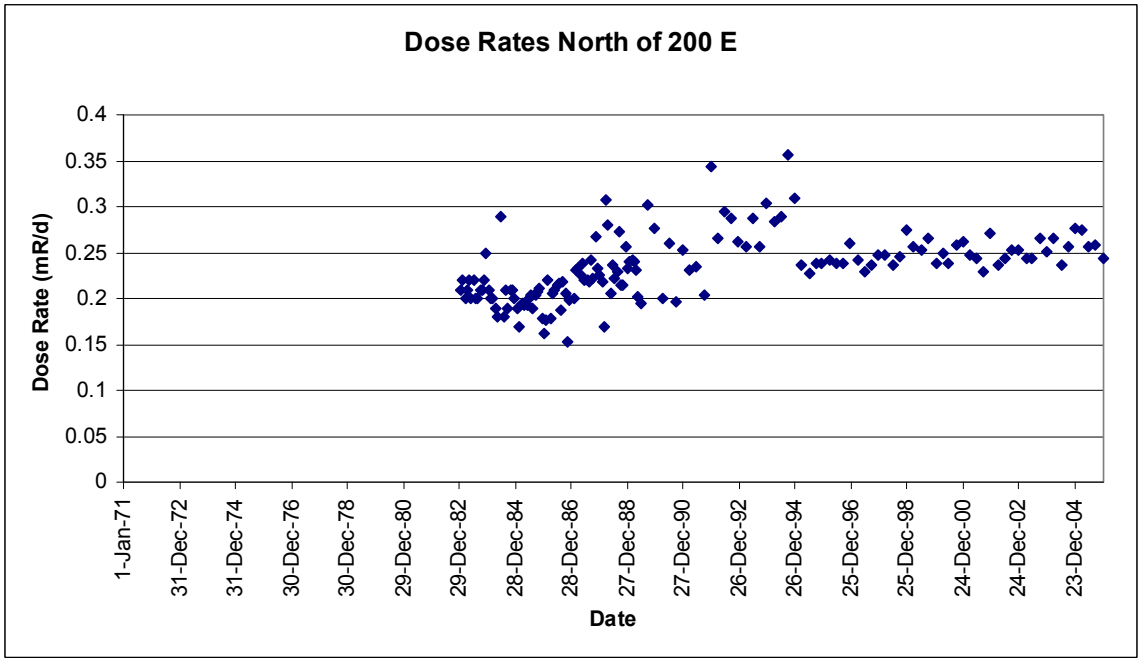


Figure A.17. Dose Rates Were Measured North of 200-East Area from January 1983 Through December 2005. This dosimeter was located near the northeast corner of the 200-East Area.

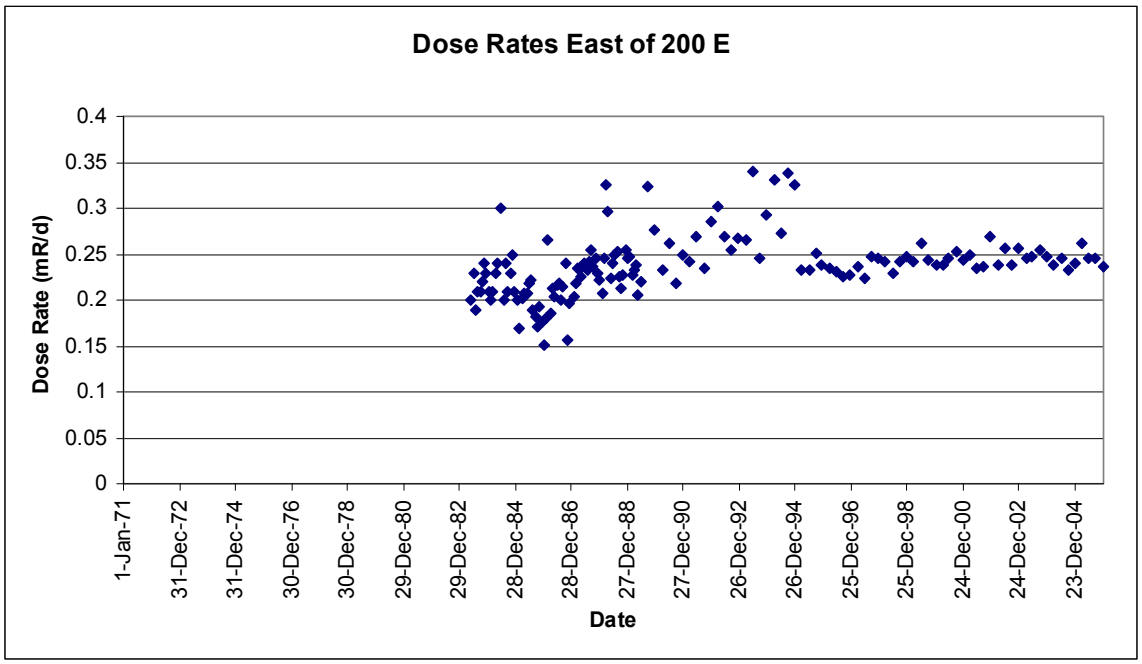


Figure A.18. Dose Rates Were Measured East of 200-East Area from May 1983 Through December 2005. The east of 200-East Area dosimeter was located approximately 50 yards east of the vitrification plant fence line, and about 0.4 mile ENE from the gate to vitrification plant.

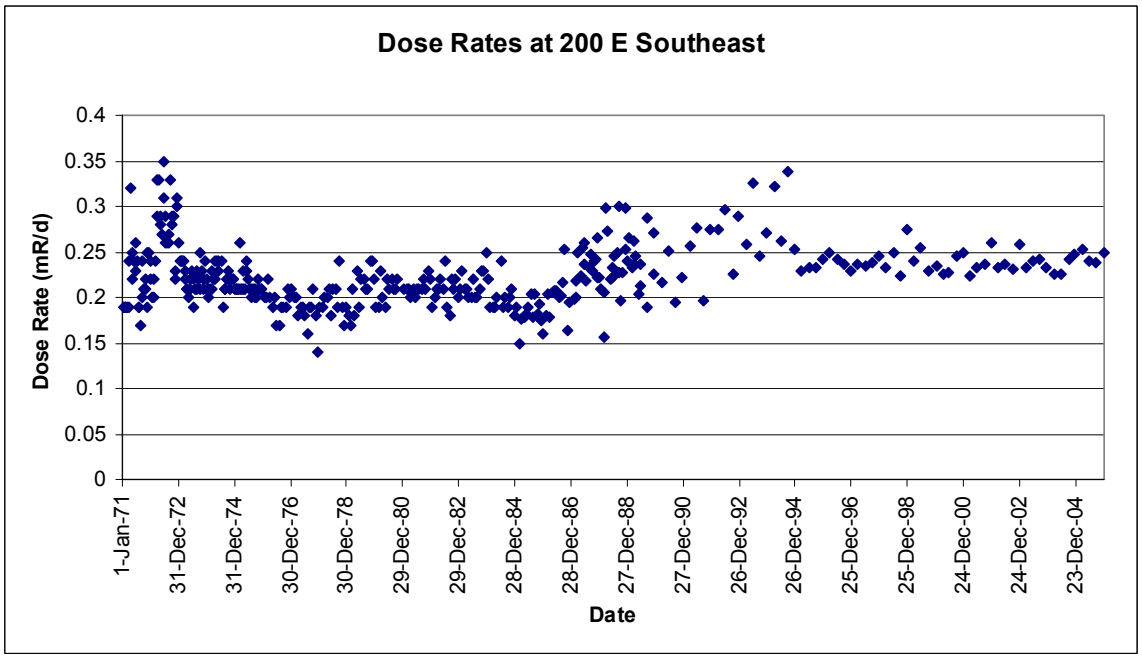


Figure A.19. Dose Rates Were Measured at 200-East Southeast (200 ESE) from January 1971 Through December 2005. The 200 ESE dosimeter was located east of the southeast corner of 200-East Area. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

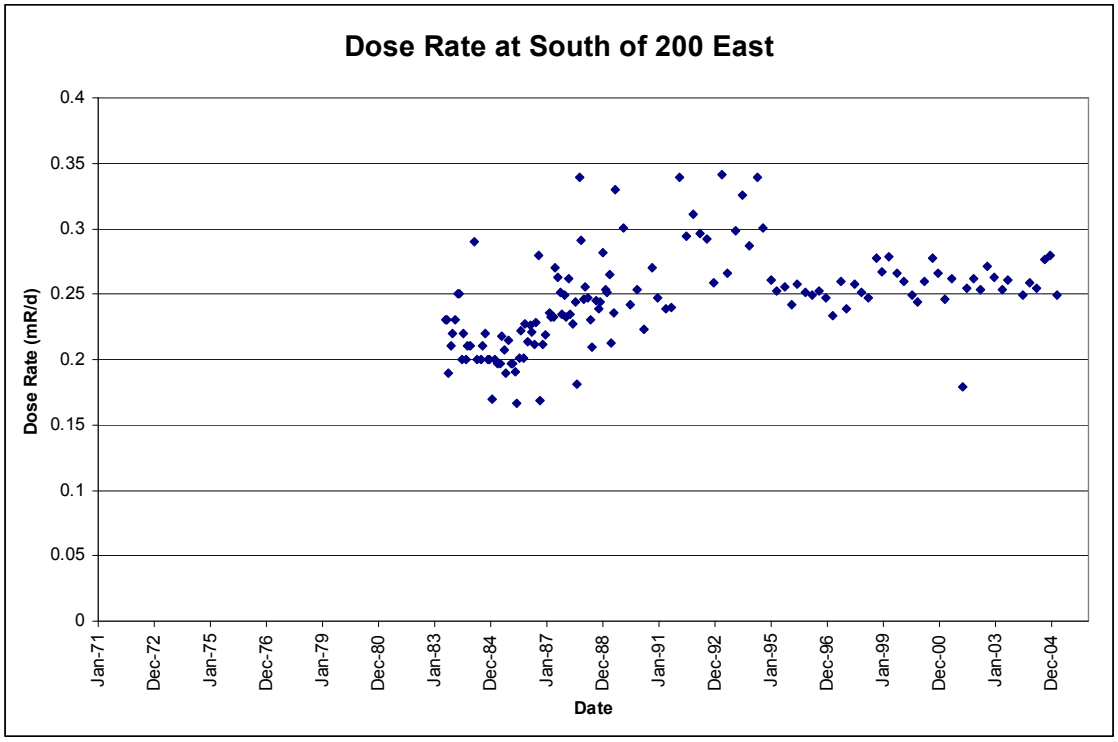


Figure A.20. Dose Rates Were Measured South of 200-East Area from January 1983 Through June 2005. This dosimeter was located south of 200-E Area.

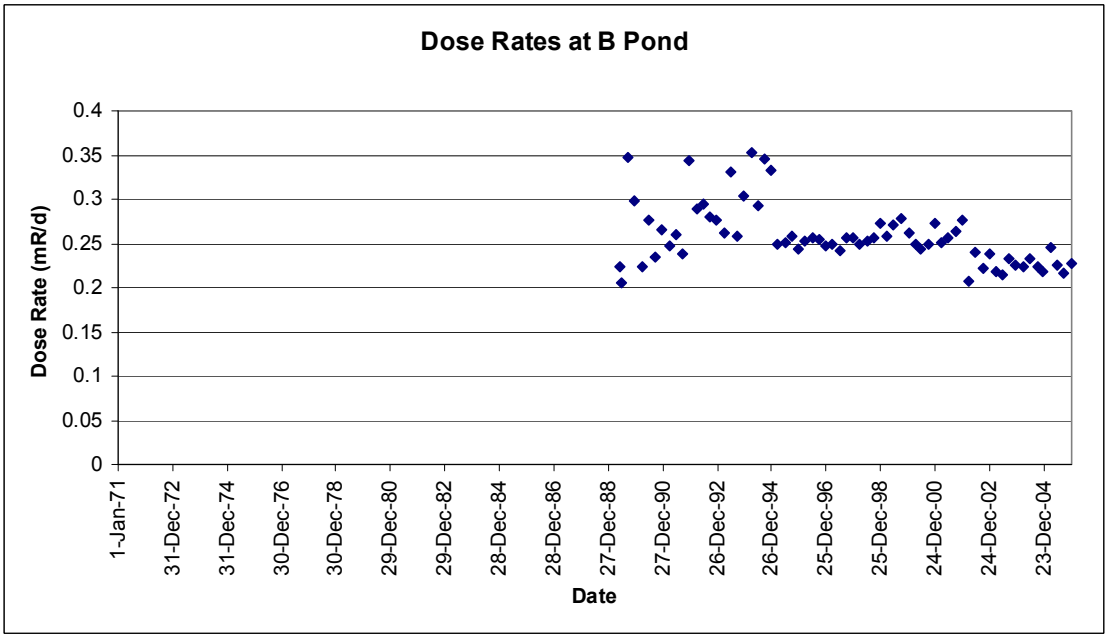


Figure A.21. Dose Rates Were Measured at B Pond Beginning in April 1989 and Ending in December 2005. The dosimeter was located south of B Pond near a small pump house (Building 6653A). No comments were found in annual reports or the HEIS database regarding the highest readings observed at the B Pond location during 1989 or 1994; however, the pond was decommissioned and backfilled in 1994 and that likely influenced the dose rate.

A.2.3 TLD Results at 300/400 Area Locations

This section contains plots of TLD data for upland TLD sampling locations for the 300/400 Areas on the Hanford Site (Figures A.22 through A.37).

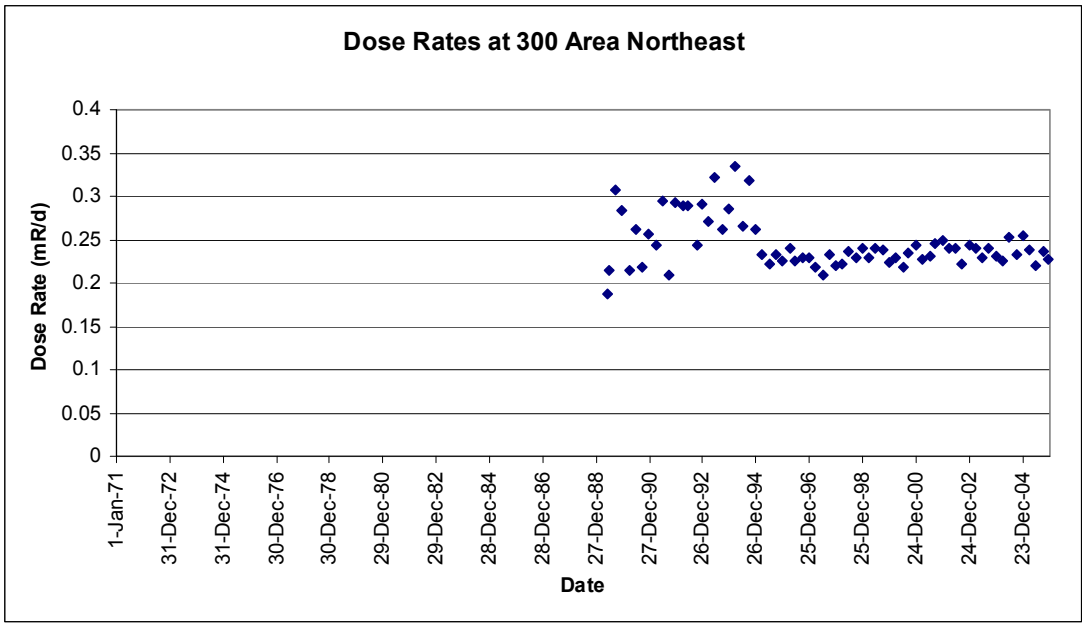


Figure A.22. Dose Rates Were Measured at 300-Area Northeast from April 1989 Through December 2005. This dosimeter was located just outside the northeast corner of the 300-Area perimeter fence.

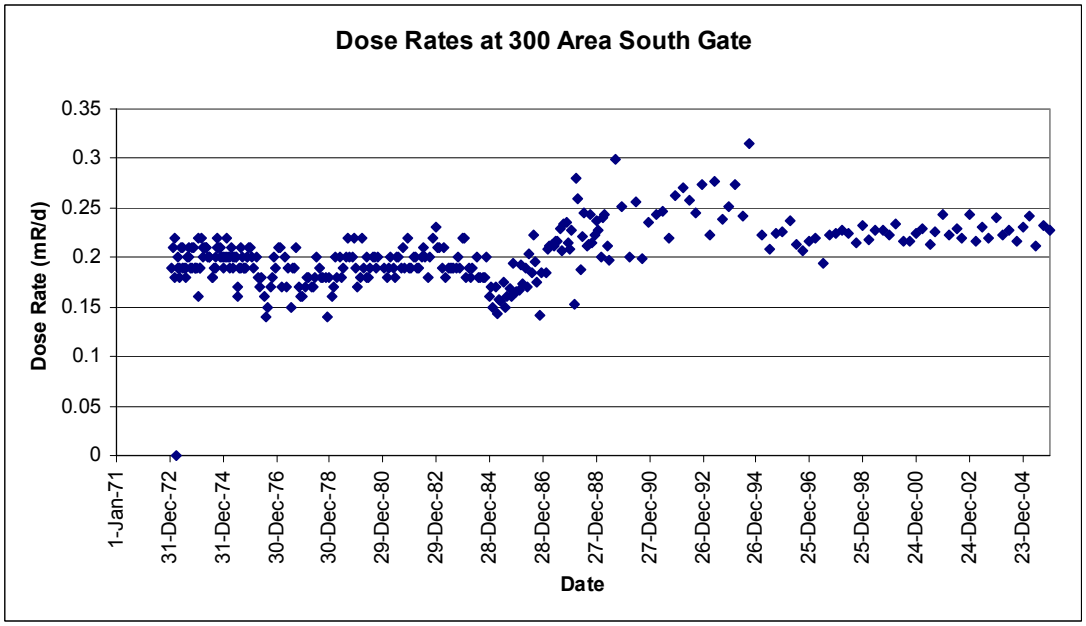


Figure A.23. Dose Rates Were Measured at the 300-Area South Gate from January 1973 Through December 2005. This dosimeter was located inside the 300-Area perimeter fence, just east of the 300-Area South Gate.

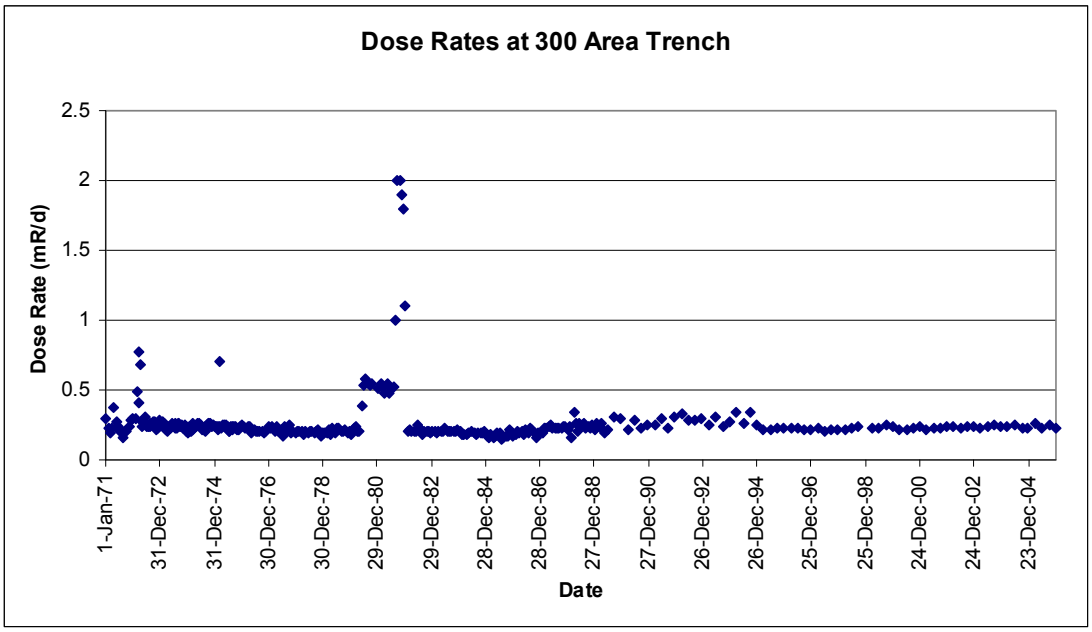


Figure A.24. Dose Rates Were Measured at the 300-Area Trench from January 1971 Through December 2005. This dosimeter was located approximately 0.3 mile east of where Route 4S crosses railroad tracks north of the 300 Area – at the south end of the 300-Area Trench. The elevated dose rates measured in 1980 and 1981 were due to the temporary storage of a radioactive steam generator nearby. The additional increase in dose rate beginning in August 1981 was attributed to the movement of shielding and equipment in preparations for relocation to a permanent facility (Sula et al. 1982).

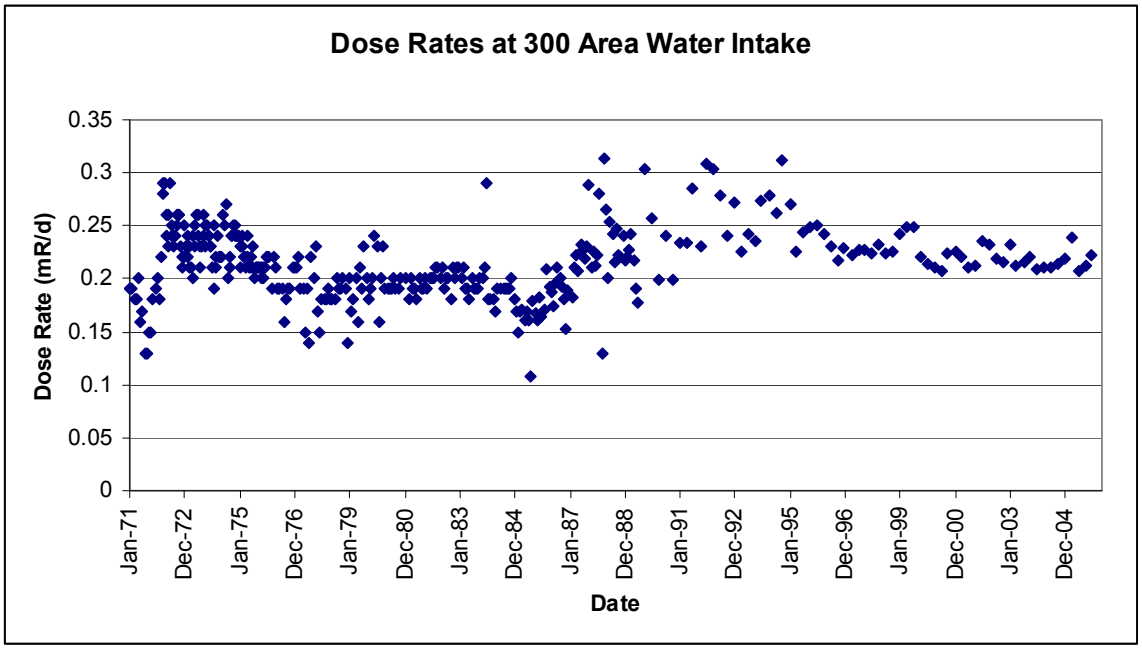


Figure A.25. Dose Rates Were Measured at 300-Area Water Intake from January 1990 Through December 2005 (this location was previously named "ACRMS - 3614-A Building" for samples collected from January 1971 through December 1989. This dosimeter was located inside the 300-Area perimeter fence near the 3614-A Building.

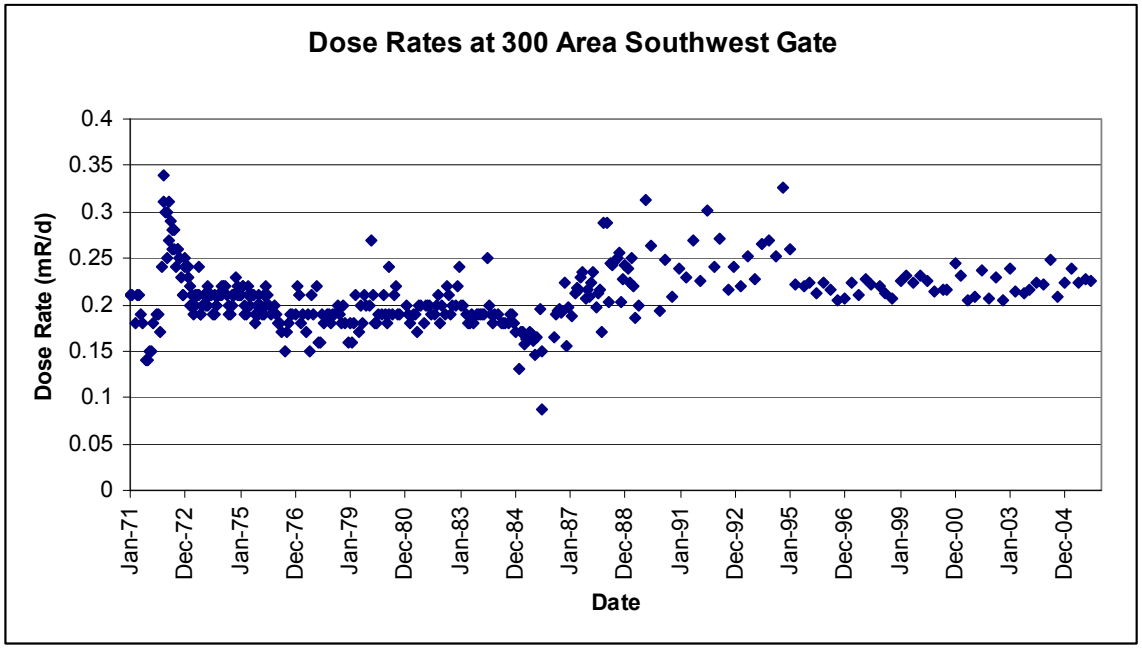


Figure A.26. Dose Rates Were Measured at the 300-Area Southwest Gate from January 1973 Through December 2005. Dose rates in this area were initially measured from 1970 to 1972 at the 320 Building location that was co-located with the air sampler approximately 50 meters to the south of the 300-Area Southwest Gate location.

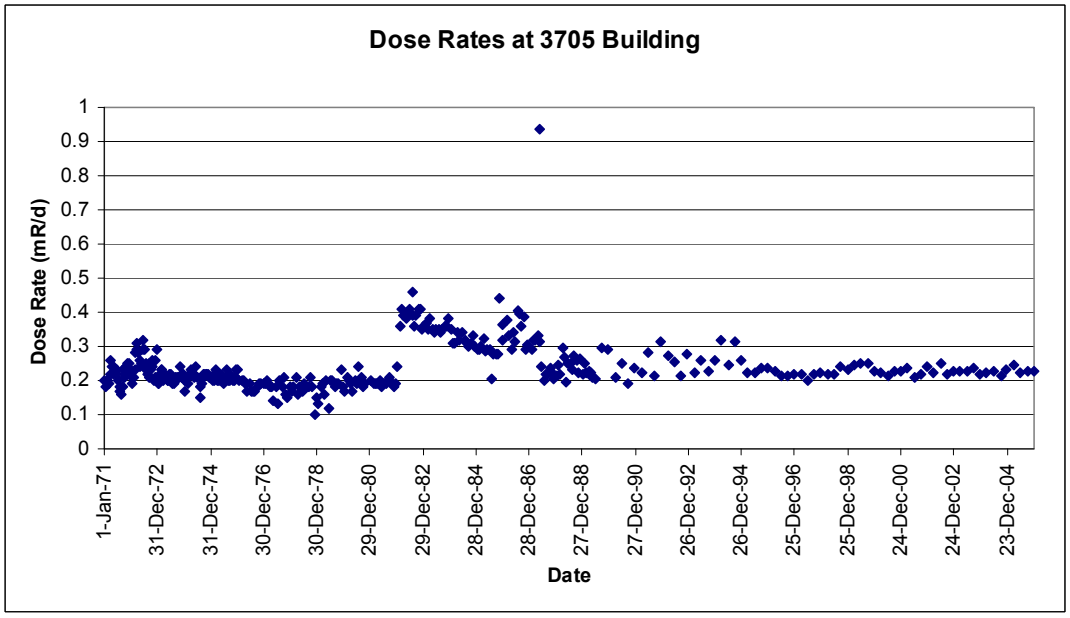


Figure A.27. Dose Rates Were Measured at the 3705 Building from January 1971 Through December 2005. No comments were found in the 1982 annual report explaining the marked increase in dose rates beginning in 1982. The single elevated dosimeter reading in May 1987 was a special dosimeter that was deployed for only 2 days when a radioactive steam generator was being moved from the 377 Building.

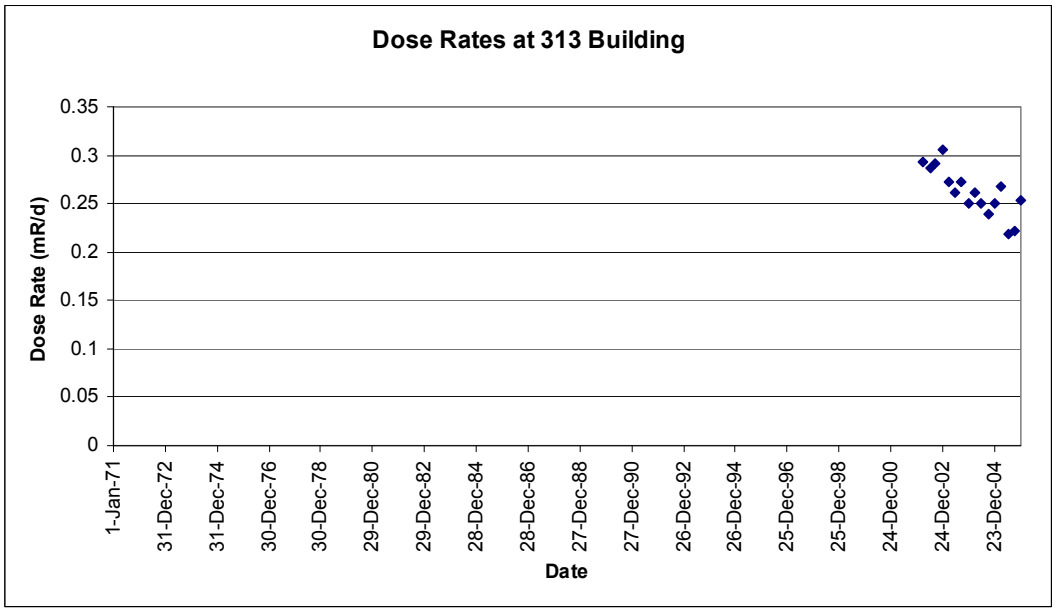


Figure A.28. Dose Rates Were Measured Near the 313 Building from the First Quarter of 2002 Through December 2005. This location was located along the 300-Area perimeter fence between the 300-A North parking lot and the 313 Building.

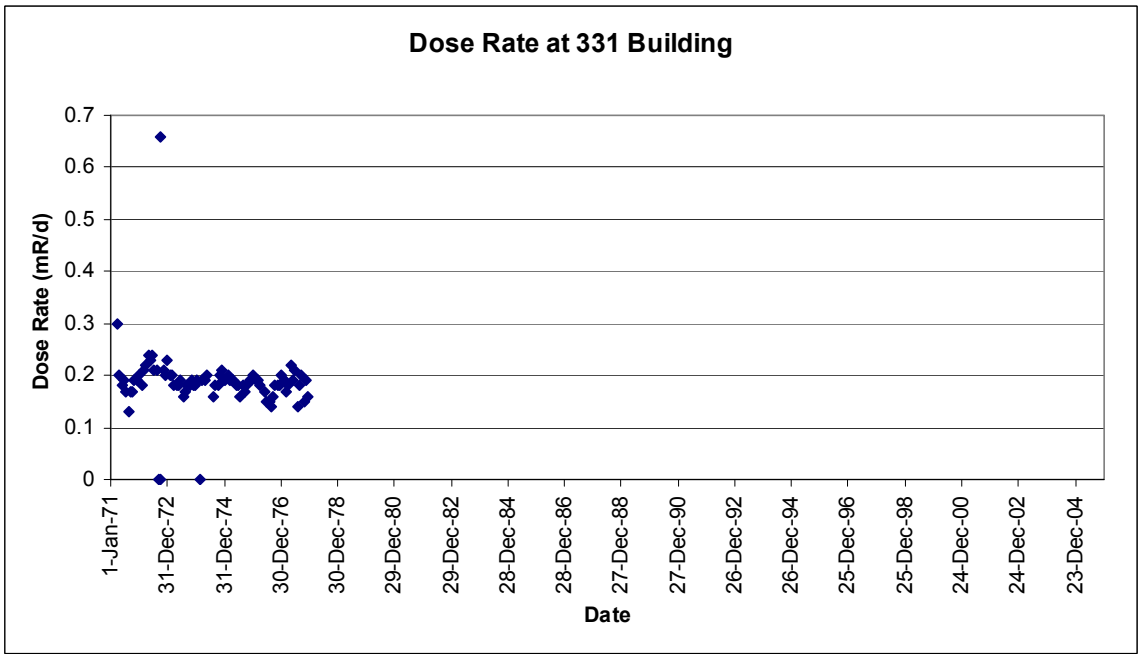


Figure A.29. Dose Rates Were Measured at the 331 Building from January 1971 Through December 1977. No comments were found in the annual reports regarding the elevated reading in October 1972.

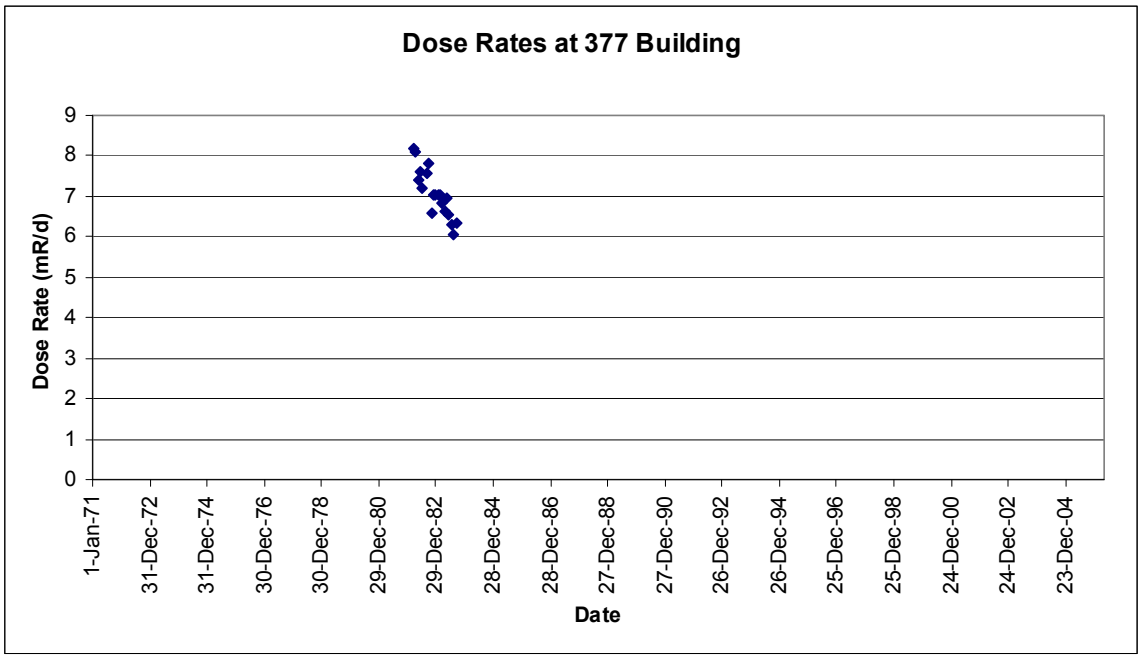


Figure A.30. Dose Rates Were Measured at the 377 Building from February 1982 Through September 1983. The elevated dosimeter readings were due to a radioactive steam generator being studied at a nearby research facility. However, due to fence line modifications eliminating potential exposure to the public this dosimeter was discontinued in September 1983 (Price et al. 1984).

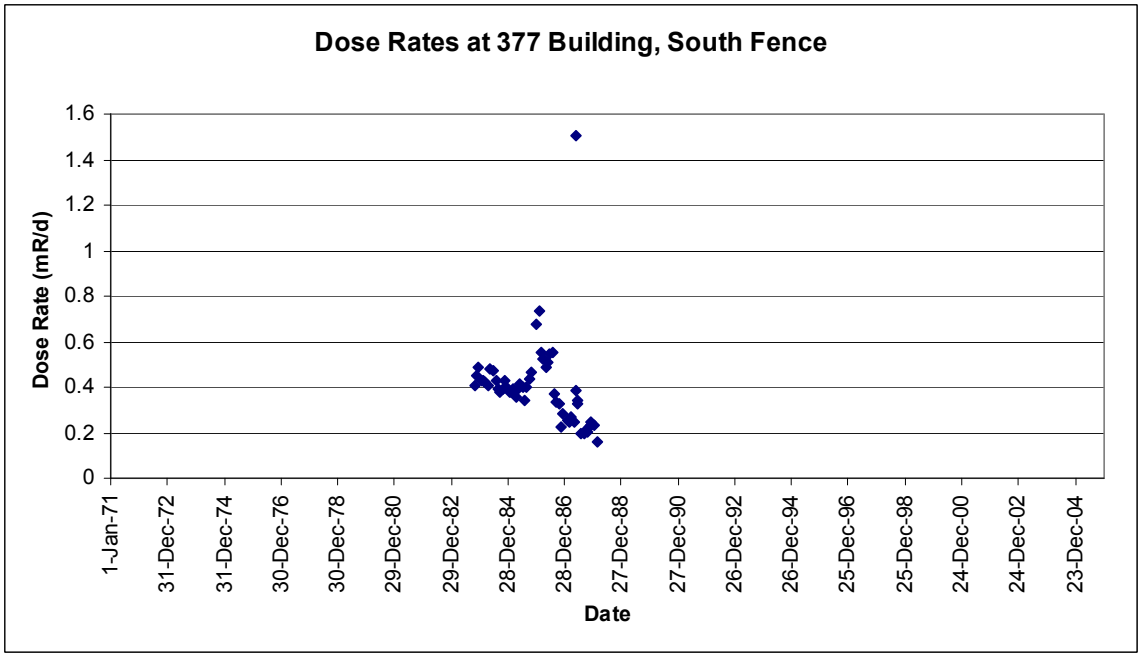


Figure A.31. Dose Rates Were Measured at the 377 Building South Fence from October 1983 Through December 1987. The single elevated dosimeter reading in May 1987 was a special dosimeter that was deployed for only 2 days while a radioactive steam generator was moved from the 377 Building.

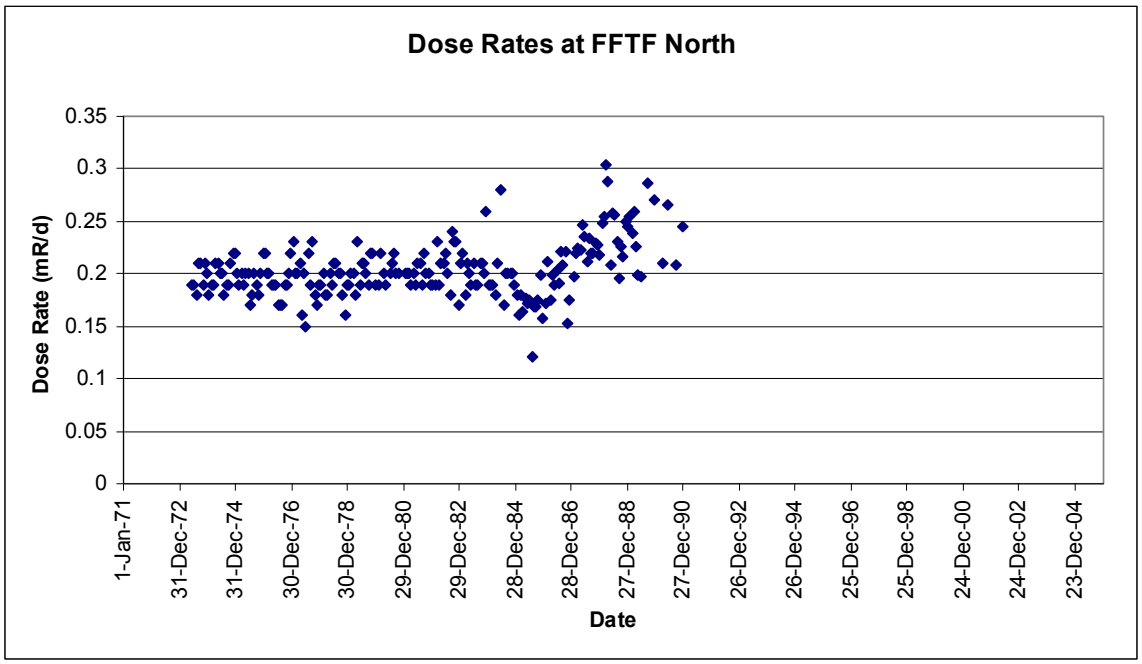


Figure A.32. Dose Rates Were Measured at the Fast Flux Test Facility (FFTF North) from May 1973 Through December 1990. This dosimeter was located approximately 0.1 mile from Route 4 South between the power line extending from FFTF toward the river and the railroad crossing.

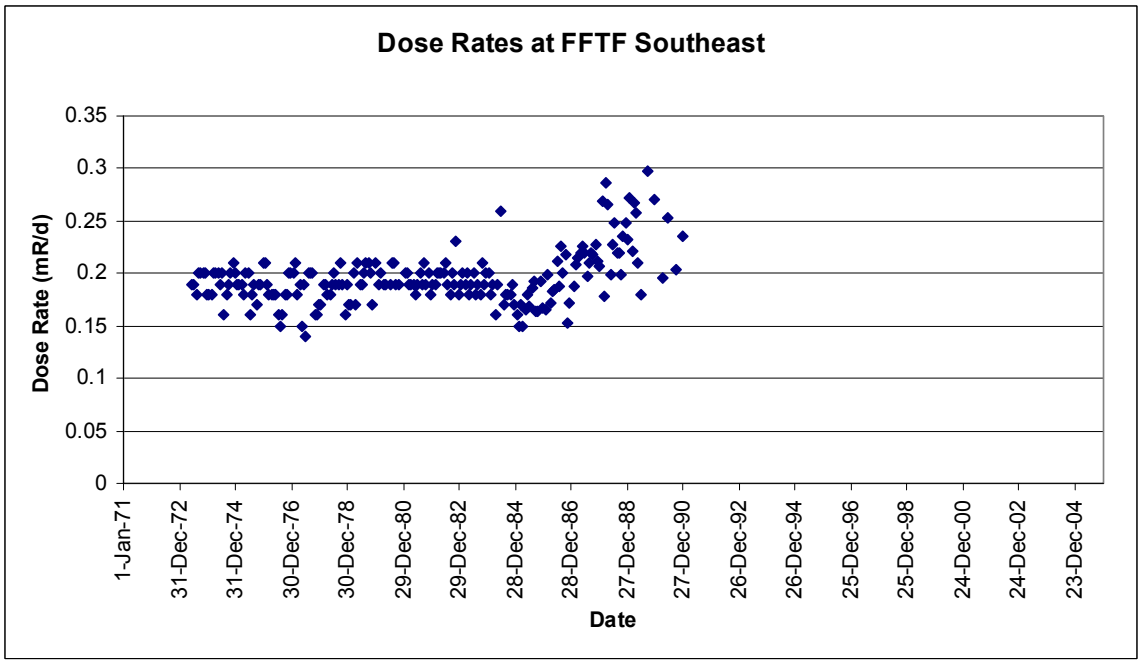


Figure A.33. Dose rates were measured at FFTF Southeast from May 1973 through December 1990. This dosimeter was located 2.7 miles north of the 300 Area West gate along Route 4 S, near gravel pits and less than 0.1 mile off Route 4 S.

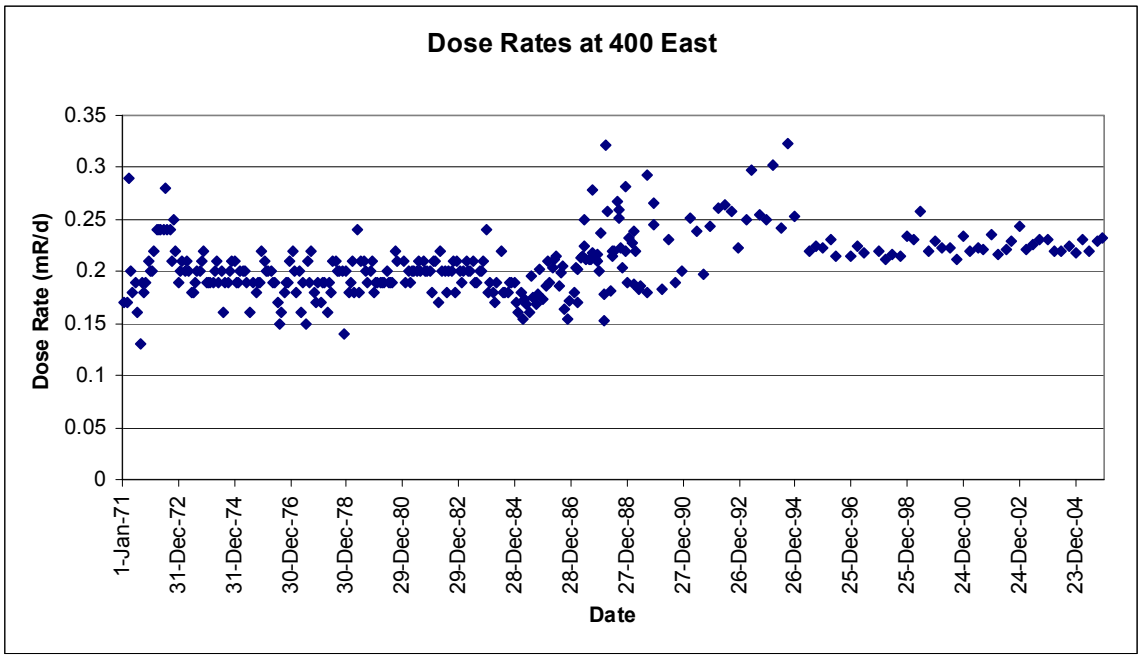


Figure A.34. Dose Rates Were Measured at 400 East from January 1971 Through December 2005. This dosimeter was located in the northwest area visitor parking lot near the main entrance gate to the Fast Flux Test Facility.

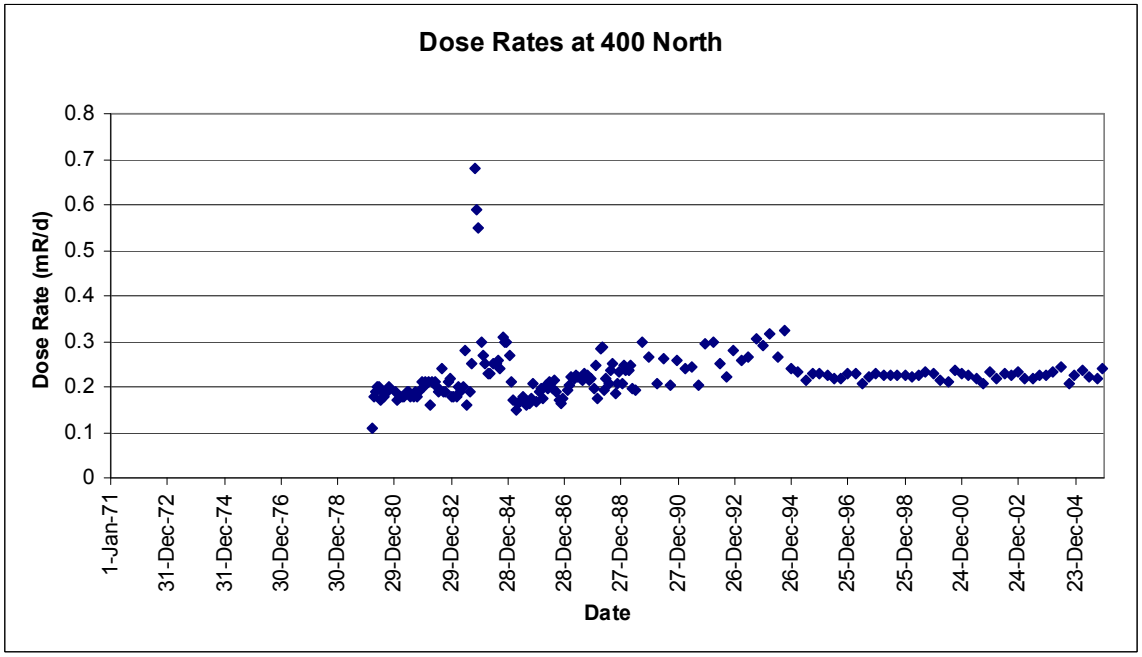


Figure A.35. Dose Rates Were Measured at 400 North from March 1980 Through December 2005. The elevated readings in fall 1983 were due to a railcar parked nearby. This dosimeter was located approximately halfway along the north perimeter fence of the Fast Flux Test Facility.

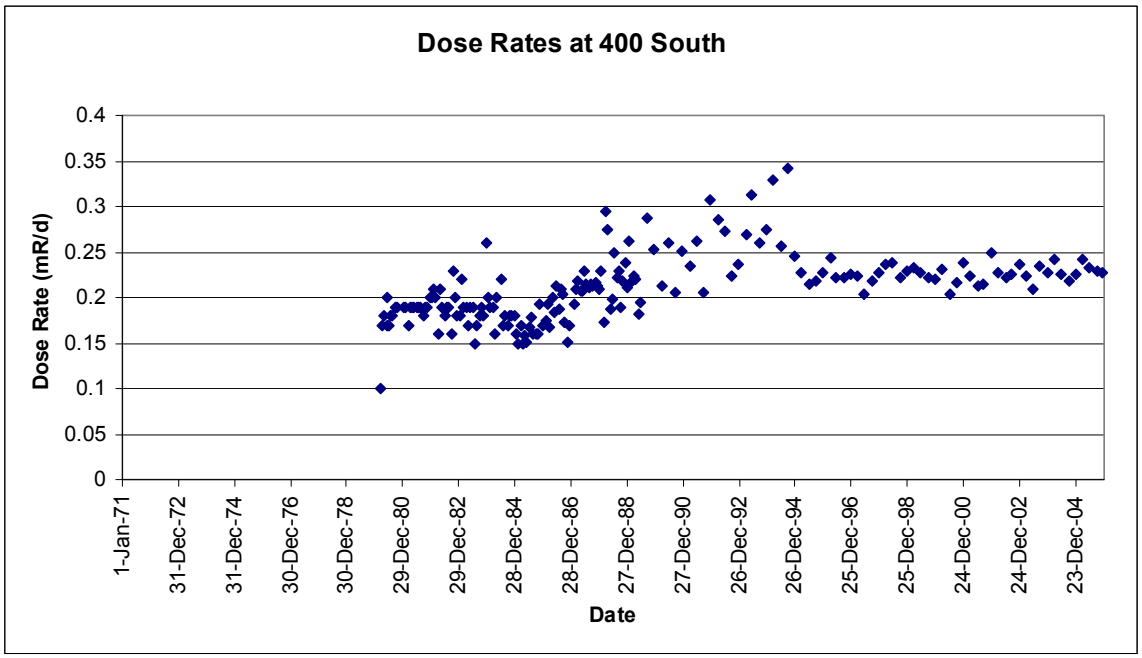


Figure A.36. Dose Rates Were Measured at 400 South from March 1980 Through December 2005. The dosimeter was located near the base of the 400-Area meteorology tower.

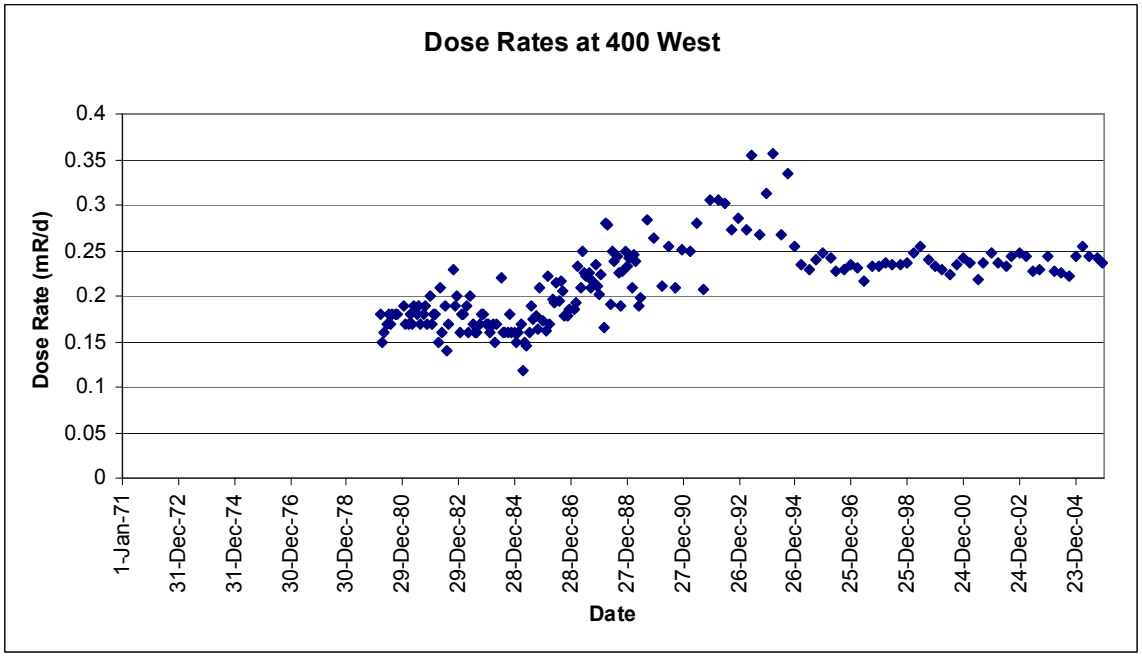


Figure A.37. Dose Rates Were Measured at 400 West from March 1980 Through December 2005. The dosimeter was located near the center of the perimeter fence on the west side of perimeter road.

A.2.4 TLDs Co-Located with the Washington State Department of Health

This section contains plots of TLD data for upland TLD sampling locations that occurred on the Hanford Site and were co-located with TLD sampling by the Washington Department of Health (Figures A.38 through A.44).

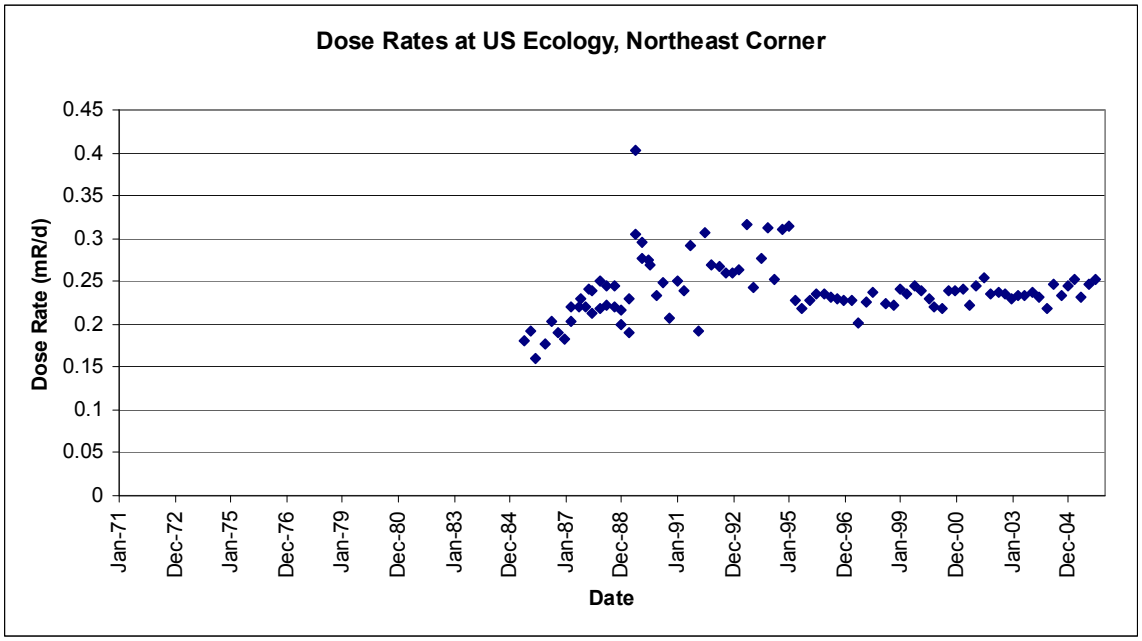


Figure A.38. Dose Rates Were Measured at US Ecology, Northeast Corner, from March 1985 Through December 2005

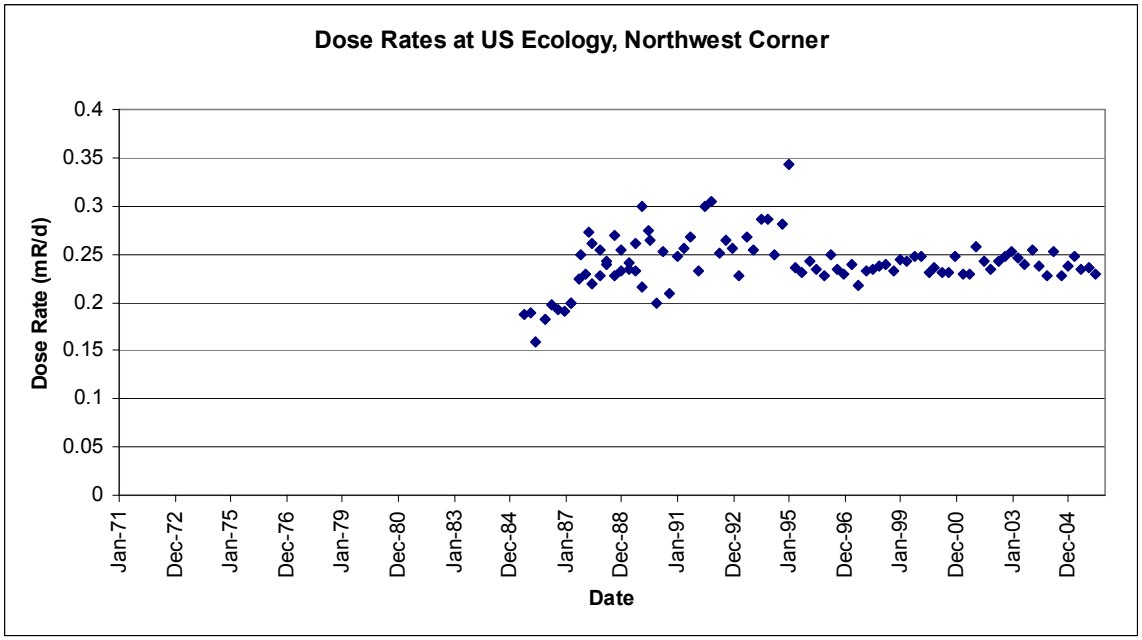


Figure A.39. Dose Rates Were Measured at US Ecology, Northwest Corner, from March 1985 Through December 2005

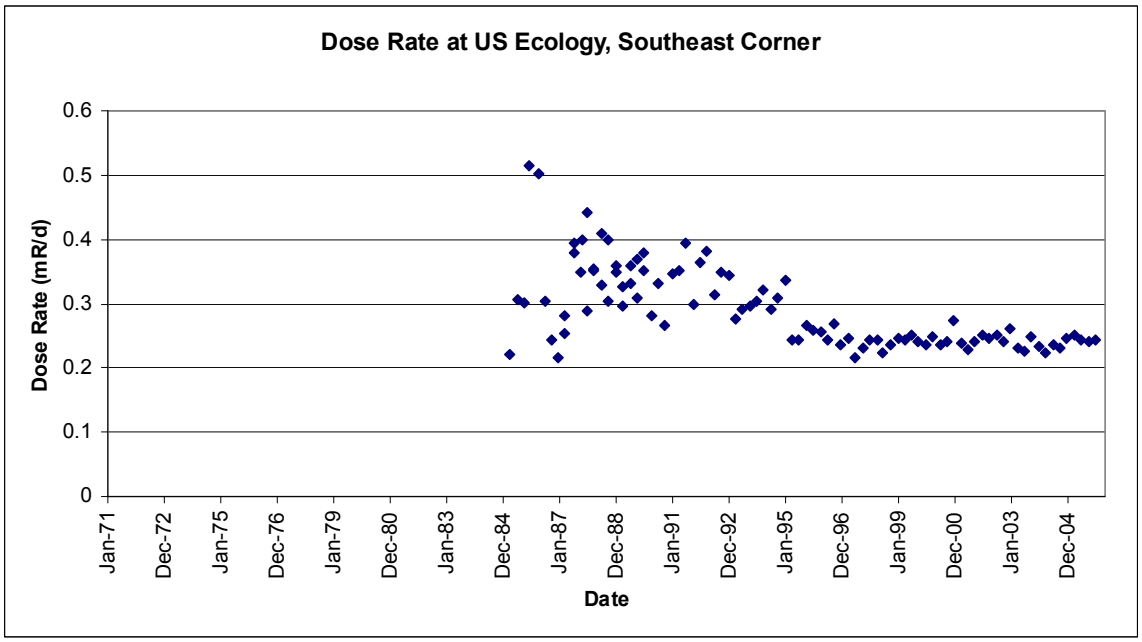


Figure A.40. Dose Rates Were Measured at US Ecology, Southeast Corner, from March 1985 Through December 2005

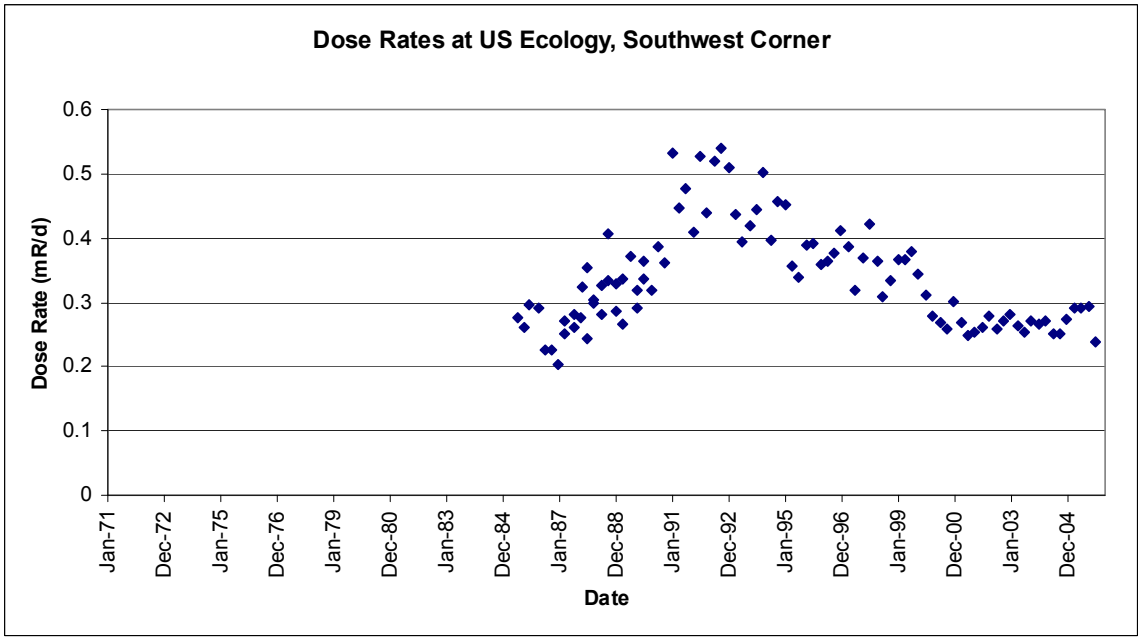


Figure A.41. Dose Rates Were Measured at US Ecology, Southwest Corner, from March 1985 Through December 2005

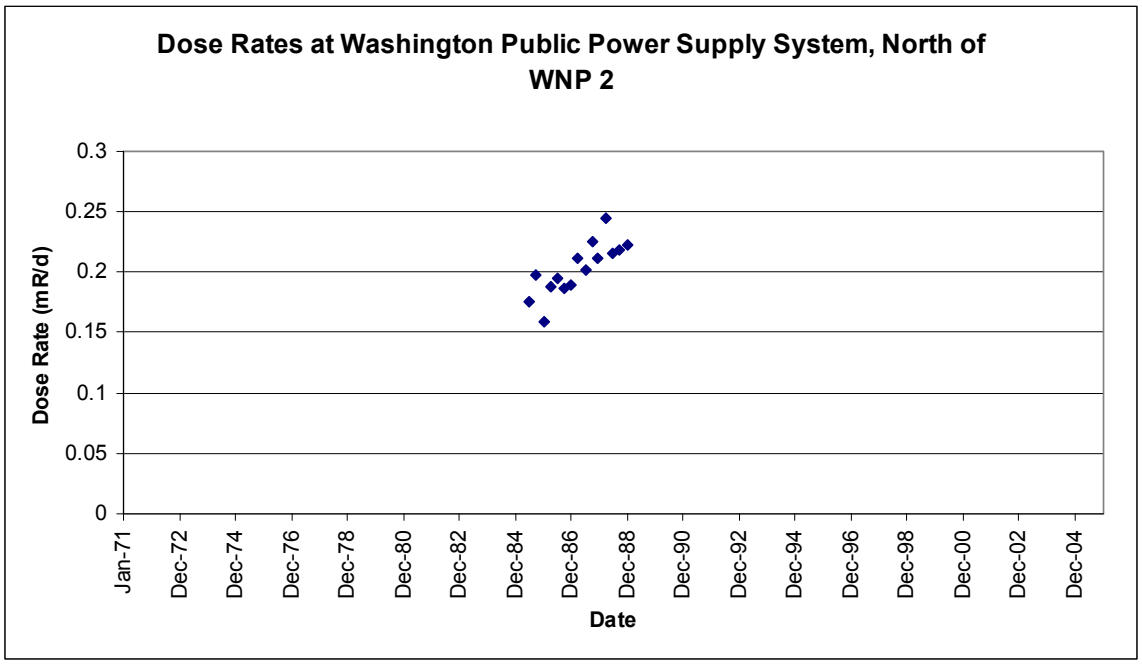


Figure A.42. Dose Rates Were Measured at the Columbia Generating Station (Operated by Energy Northwest, formerly WPPSS), North of WNP2, from March 1985 Through December 1988

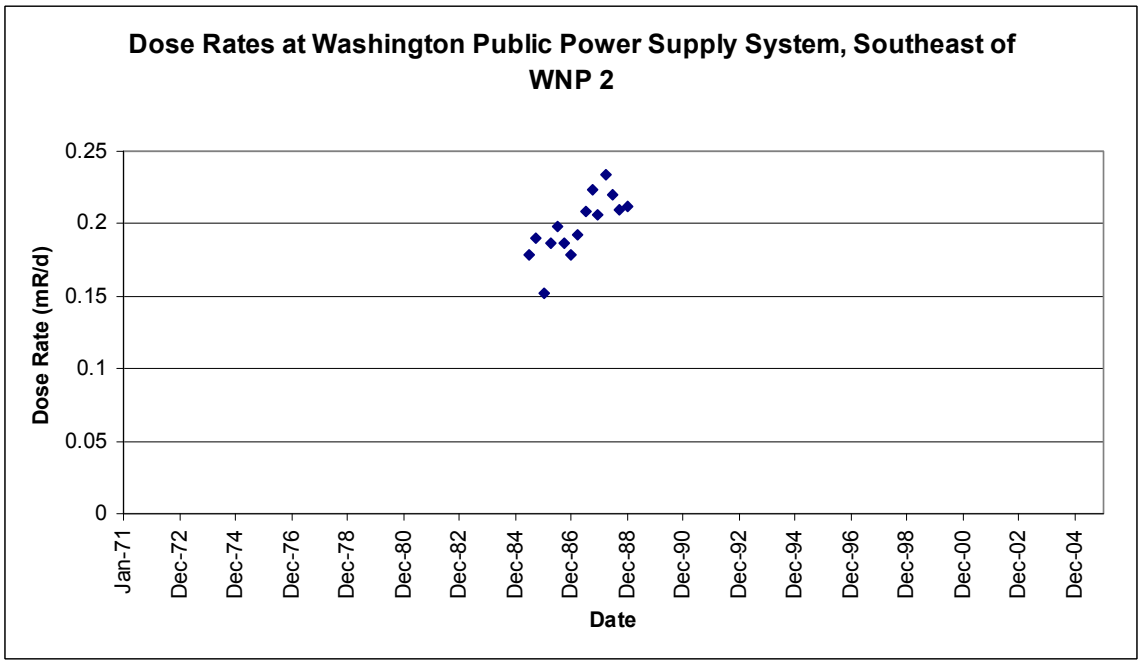


Figure A.43. Dose Rates Were Measured at the Columbia Generating Station (Operated by Energy Northwest, formerly WPPSS), Southeast of WNP2, from March 1985 Through December 1988

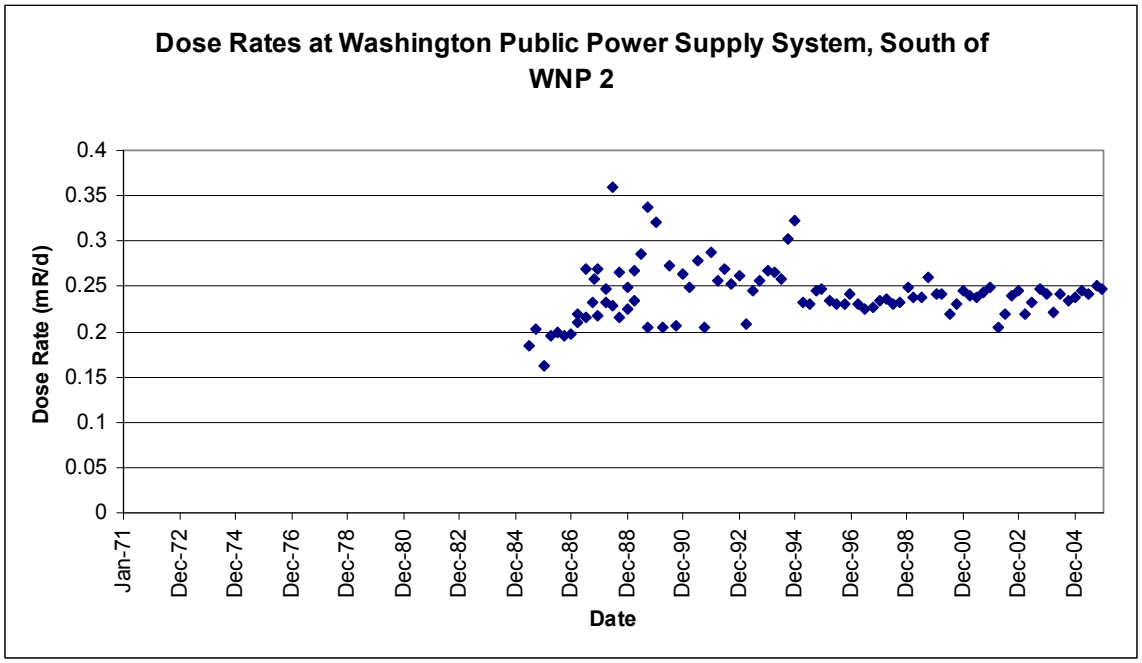


Figure A.44. Dose Rates Were Measured at the Columbia Generating Station (Operated by Energy Northwest, formerly WPPSS), South of WNP2, from March 1985 Through December 2005. This dosimeter was located about 0.7 mile off Route 4 south along the railroad tracks that go between the Fast Flux Test Facility and the Columbia Generating Station.

A.2.5 TLD Results at 600 Area Locations

This section contains plots of TLD data for upland TLD sampling locations for the 600 Area on the Hanford Site (Figures A.45 through A.53).

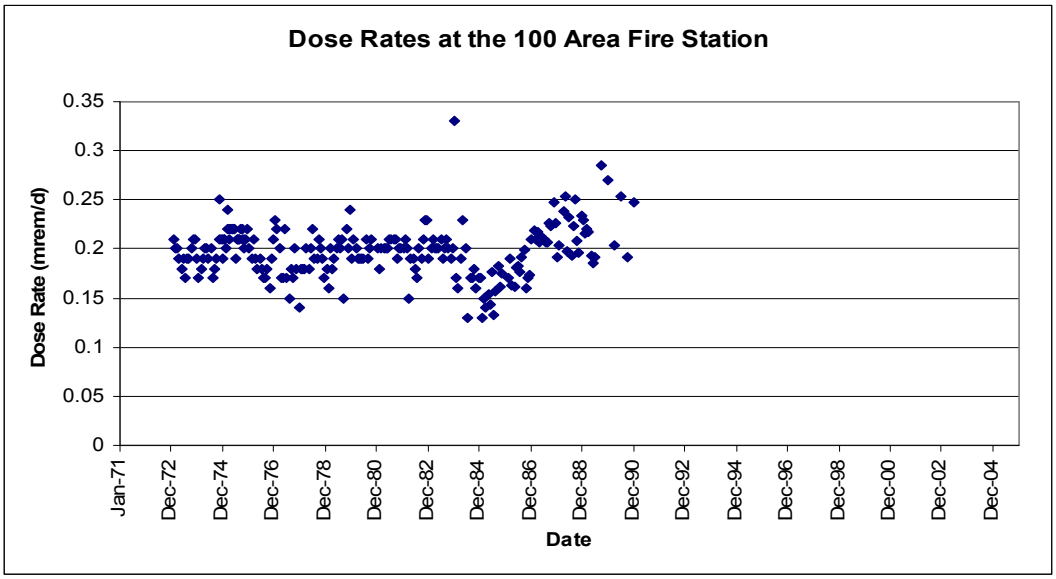


Figure A.45. Dose Rates at the 100-Area Fire Station Were Measured from January 1973 Through December 1990. The dosimeter was located on the northwest corner of the intersection of 4N and Route 1. No comments were found in annual reports regarding the highest observed reading at 100-Area Fire Station in 1984.

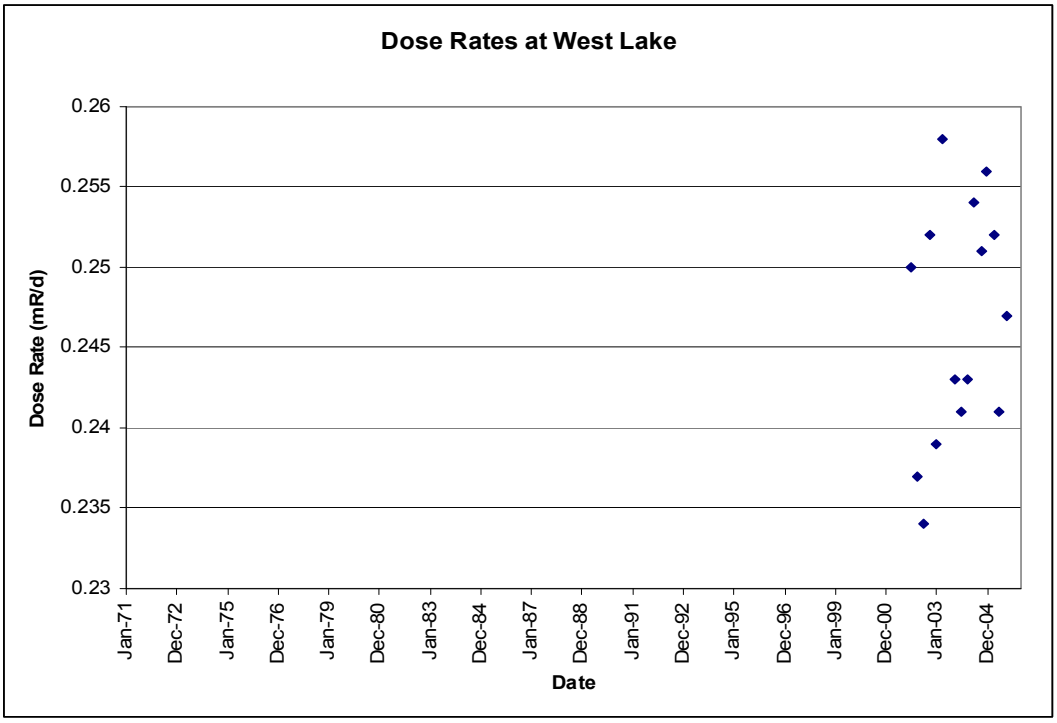


Figure A.46. Dose Rates at West Lake Were Measured from December 2001 Through December 2005

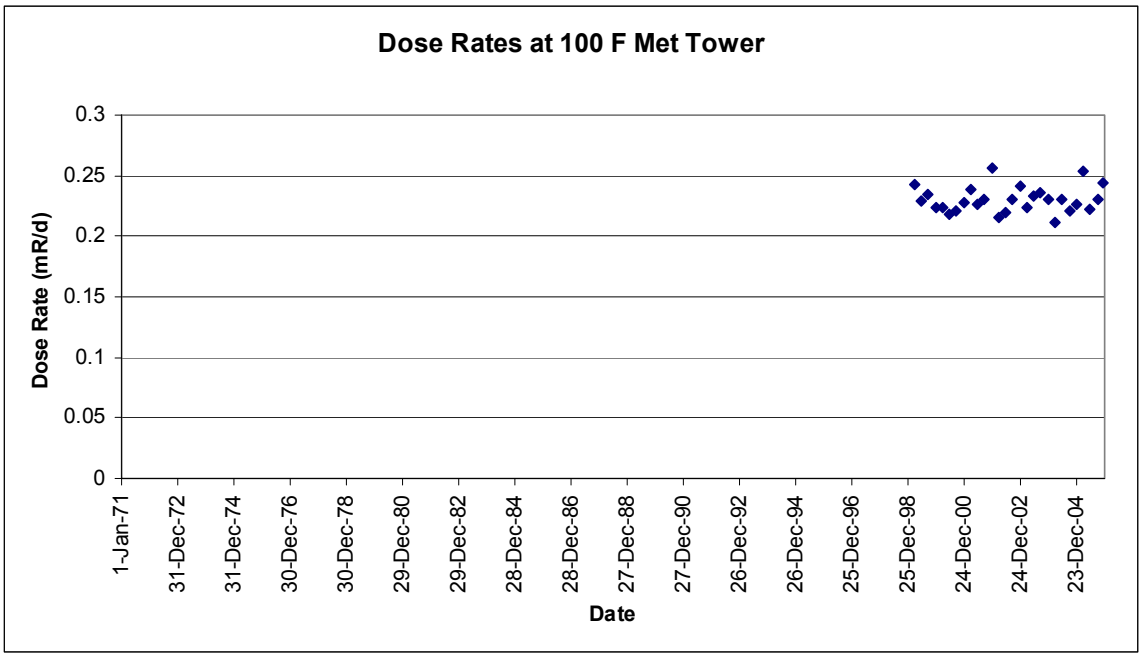


Figure A.47. Dose Rates Were Measured at the 100-F Meteorology Monitoring Station from January 1999 Through December 2005. The dosimeter was located on the southwest corner of the intersection of Route 2 North and Route 1. No comments were found regarding dose rates observed at the 100-F Area Meteorology Monitoring Station TLD location.

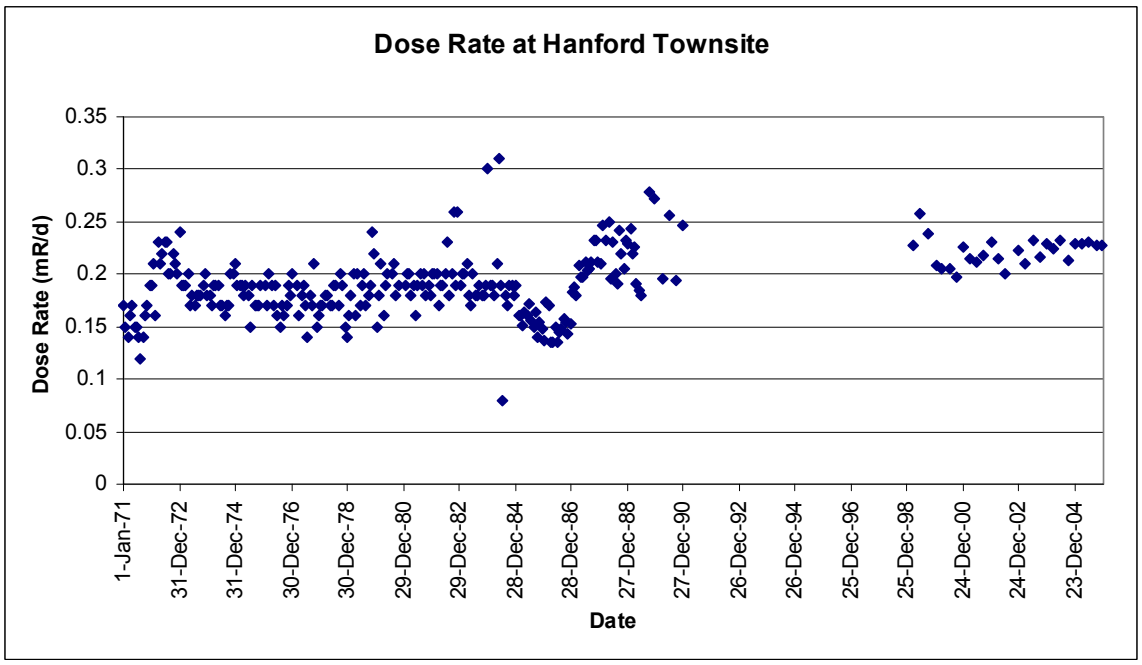


Figure A.48. Dose Rates Were Measured at the Hanford Townsite from January 1971 Through December 1990 When the Surveillance was Discontinued Until January 1999 Then Re-Established and Continued Through December 2005. This dosimeter was located along Route 2 North, about 0.8 mile north of the Route 11-A and Route 2 South intersection, about 100 meters off the road.

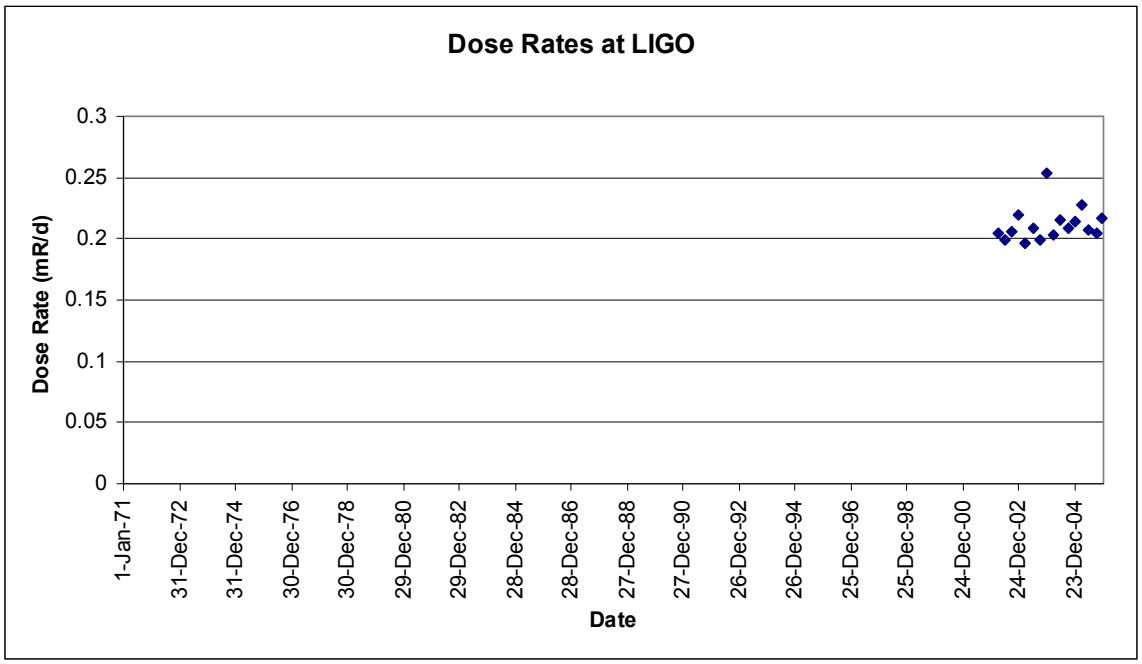


Figure A.49. Dose Rates Were Measured at the Laser Interferometer Gravitational Wave Observatory (LIGO) from January 2002 Through December 2005. It was established to monitor doses for non-DOE employees working at the facility.

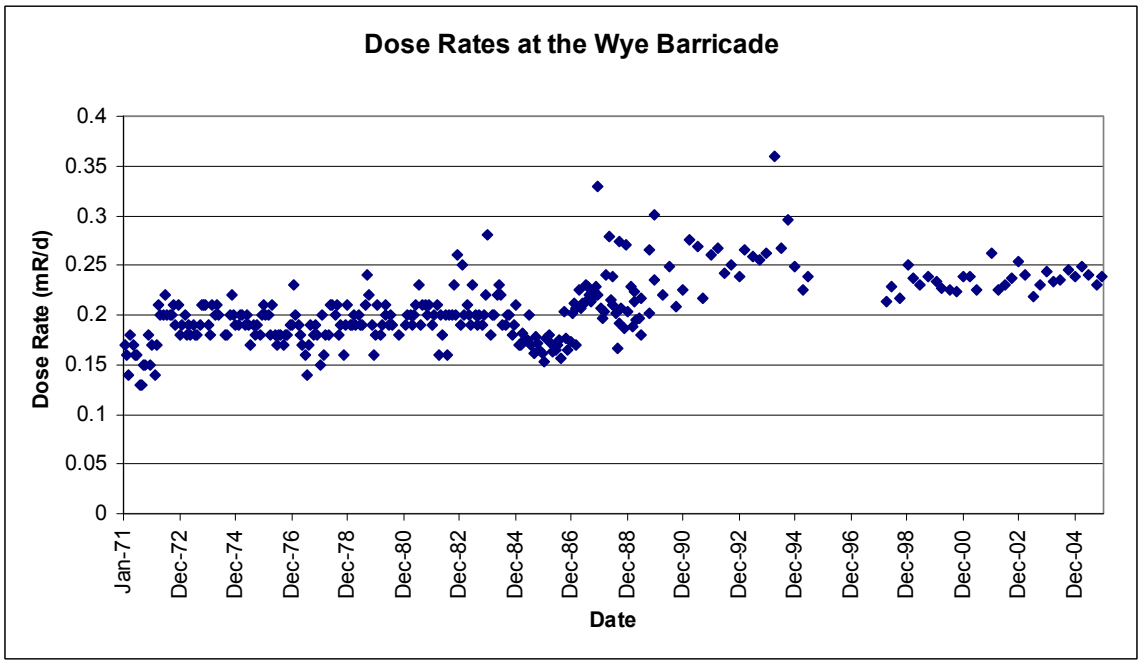


Figure A.50. Dose Rates Were Measured at the Wye Barricade from January 1971 Through June 1995, Then Restarted in January 1997 and Continued Through December 2005. No comments were made in the 1994 annual report (Dirkes and Hanf 1995) regarding the slightly elevated quarterly reading during the first quarter of 1994.

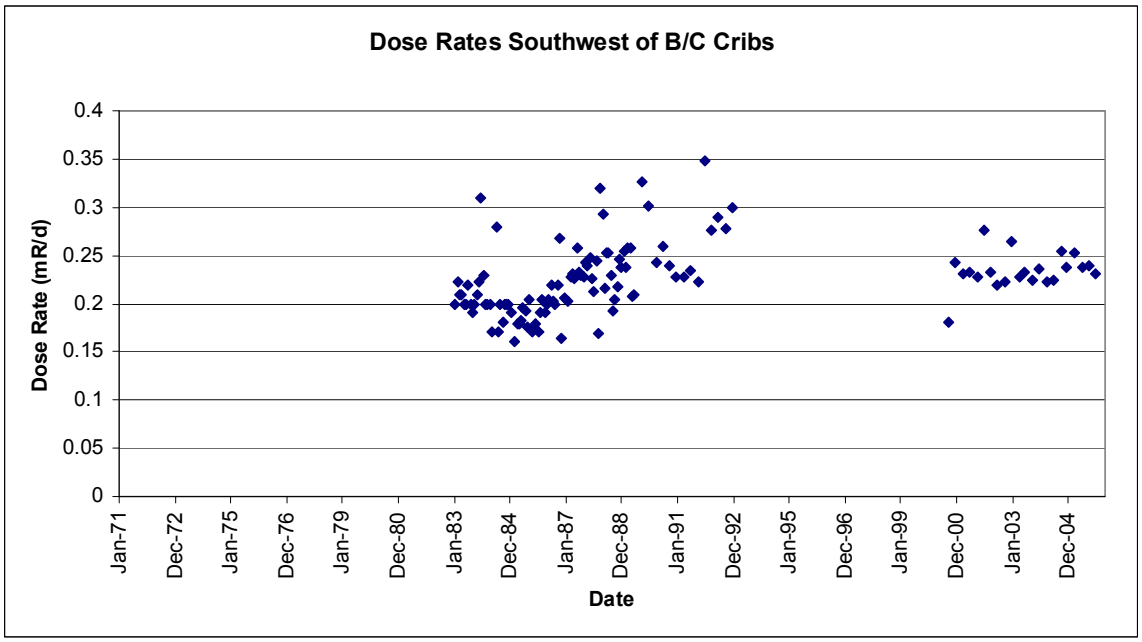


Figure A.51. Dose Rates Were Measured Southwest of the B/C Cribs from December 1982 Through December 1992, Then Resumed Again in August 2000 and Continued Until December 2005

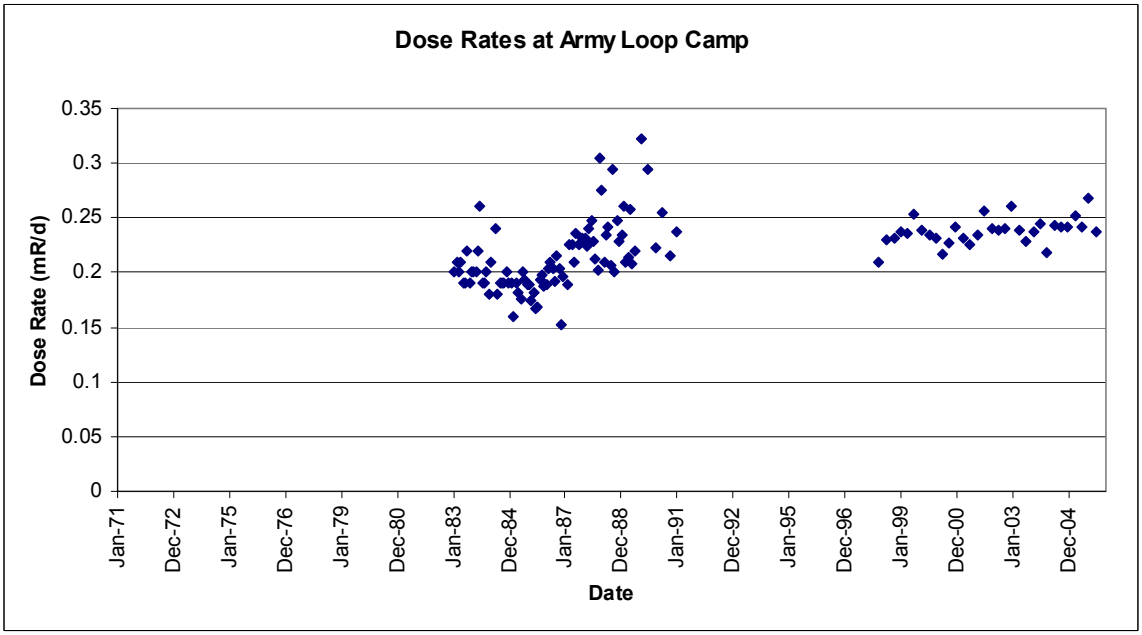


Figure A.52. Dose Rates Were Measured at Army Loop Camp from January 1983 Through December 1990 and Then Again from January 1998 Through December 2005. The dosimeter was located approximately 0.6 mile north of the old Army Loop Camp, on the east side of Route 3. No comments were found in annual reports or the HEIS database regarding the highest reading observed at the Army Loop Camp TLD location during 1989.

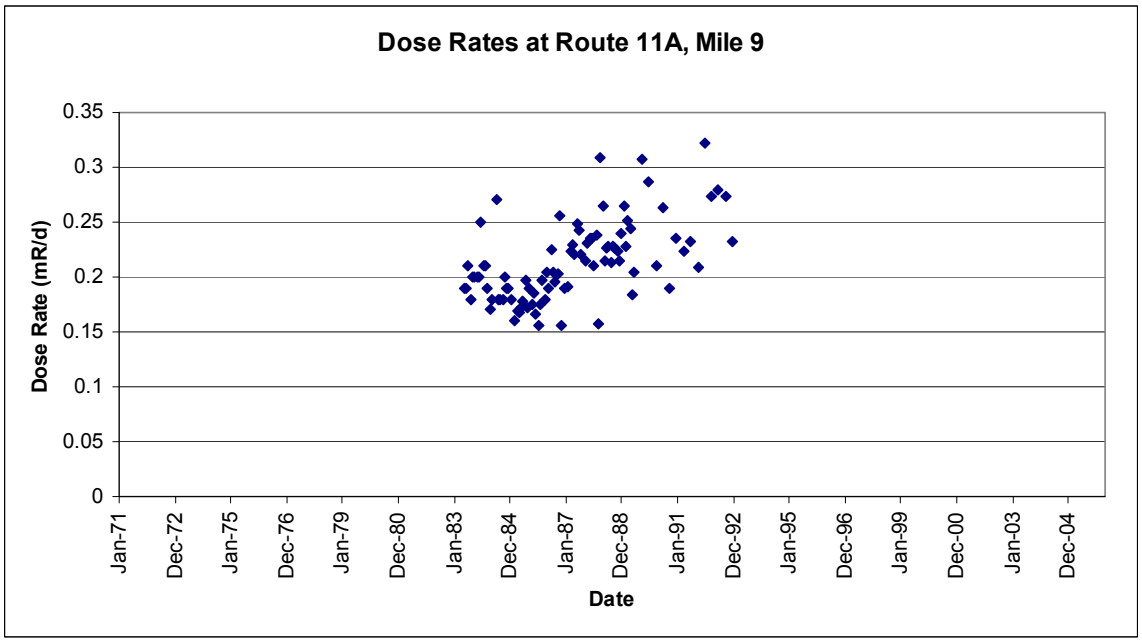


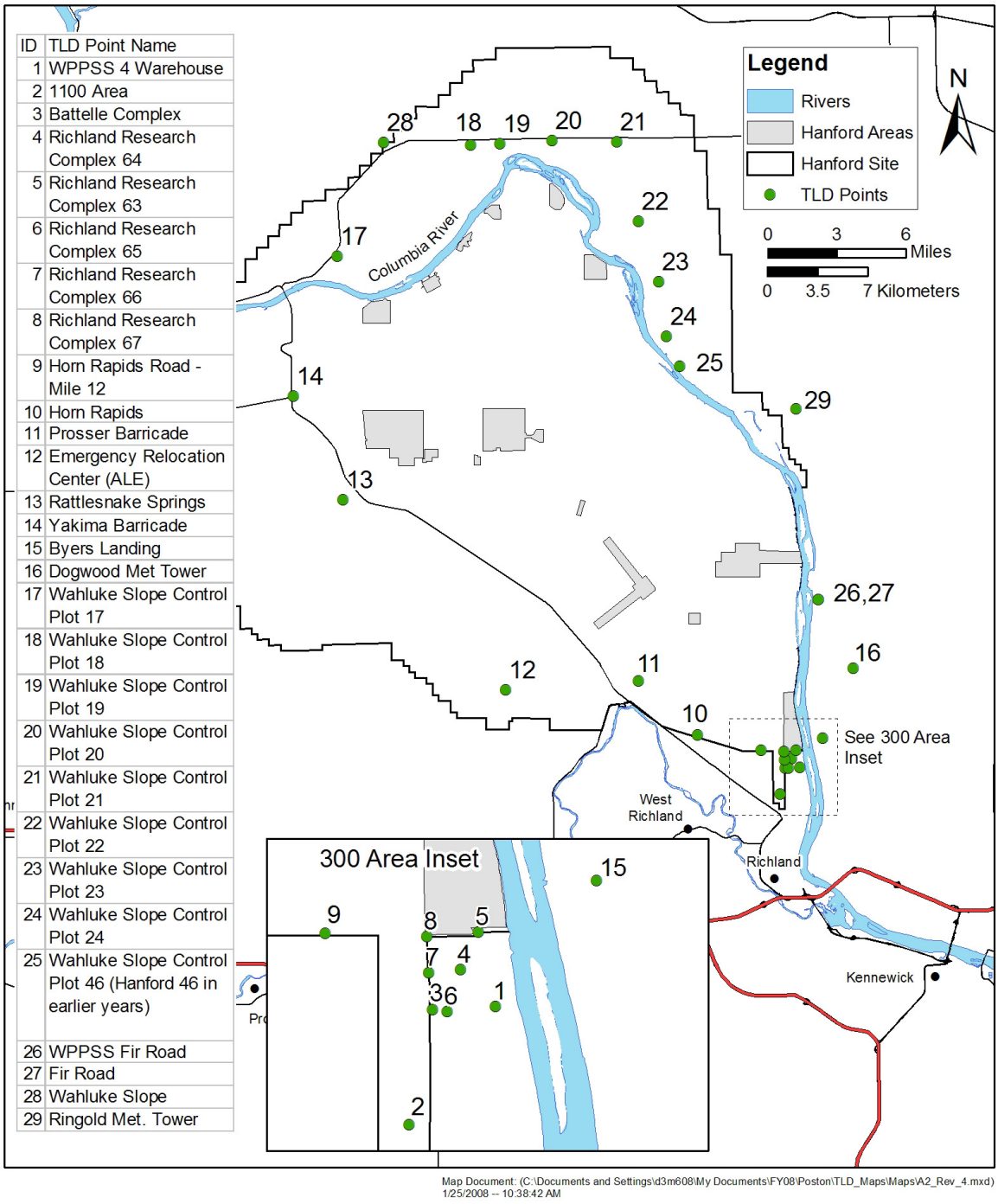
Figure A.53. Dose Rates Were Measured at Route 11A, Mile 9 from April 1983 to December 1992

A.3 Offsite Upland TLD Locations

This section of Appendix A contains graphs of offsite TLD results as reported in the HEIS database from January 1971 through December 2005. For some locations, surveillance of external radiation measurements was collected for only a few years. Perimeter, nearby community, and distant community TLDs were also co-located with air surveillance sampling locations (Figures A.54 and A.55). Over the years, depending on design configurations, TLD locations were grouped at the perimeter and in the southeast quadrant (early to mid-1970s) that eventually gave way to perimeter and community classification schemes. As a rule of thumb, perimeter locations were located on the perimeter or within DOE-owned buffer zones (Wahluke Slope or the Fitzner/Eberhardt Arid Lands Ecology Reserve (ALE), or on adjoining land at distances generally less than 10 miles from the Columbia River or Highway 240/24 on the west side of the site. Locations situated between 10 and 20 miles from these boundaries were categorized as nearby communities and those greater than 20 miles from these boundaries were viewed as distant communities.

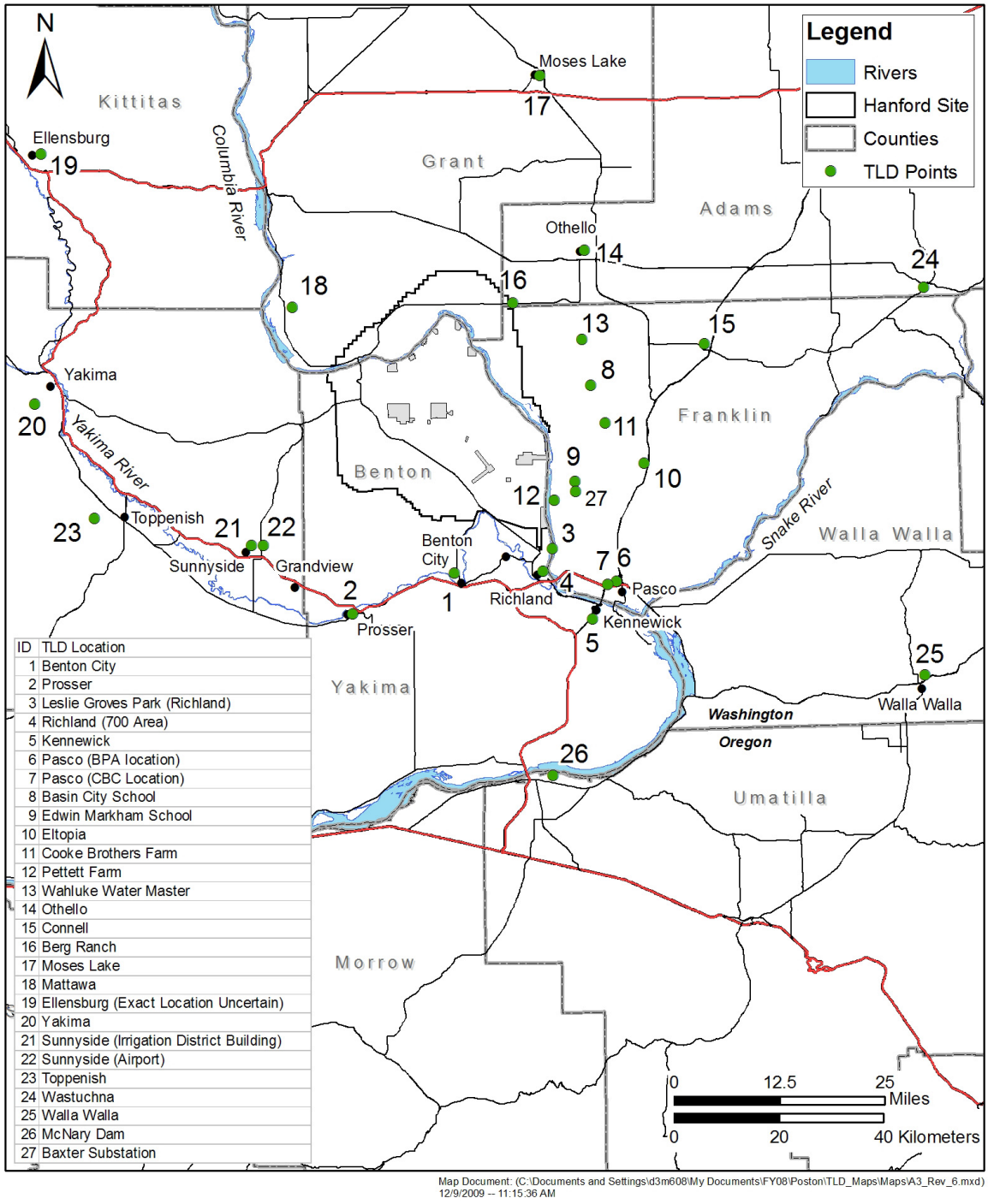
There also was a system of control plots located around the site during the 1960s and 1970s that provided soil and vegetation samples. Some of these were also used for deployment of TLDs on the Wahluke Slope and a series designated as the Richland Research Complex control plots located around the Battelle campus.

GPS coordinates were collected at sites in operation from the mid-1990s through 2005 (Table A.2). For sites that had been closed prior to this time, GPS coordinates were determined if sufficient information was available to identify the location by earlier locations manuals, reports and publicly available mapping software (Google, Inc. 2009).



ID	TLD Point Name
1	WPPSS 4 Warehouse
2	1100 Area
3	Battelle Complex
4	Richland Research Complex 64
5	Richland Research Complex 63
6	Richland Research Complex 65
7	Richland Research Complex 66
8	Richland Research Complex 67
9	Horn Rapids Road - Mile 12
10	Horn Rapids
11	Prosser Barricade
12	Emergency Relocation Center (ALE)
13	Rattlesnake Springs
14	Yakima Barricade
15	Byers Landing
16	Dogwood Met Tower
17	Wahluke Slope Control Plot 17
18	Wahluke Slope Control Plot 18
19	Wahluke Slope Control Plot 19
20	Wahluke Slope Control Plot 20
21	Wahluke Slope Control Plot 21
22	Wahluke Slope Control Plot 22
23	Wahluke Slope Control Plot 23
24	Wahluke Slope Control Plot 24
25	Wahluke Slope Control Plot 46 (Hanford 46 in earlier years)
26	WPPSS Fir Road
27	Fir Road
28	Wahluke Slope
29	Ringold Met. Tower

Figure A.54. Location of Perimeter TLD Sampling Locations



ID	TLD Location
1	Benton City
2	Prosser
3	Leslie Groves Park (Richland)
4	Richland (700 Area)
5	Kennewick
6	Pasco (BPA location)
7	Pasco (CBC Location)
8	Basin City School
9	Edwin Markham School
10	Eltopia
11	Cooke Brothers Farm
12	Pettett Farm
13	Wahluke Water Master
14	Othello
15	Connell
16	Berg Ranch
17	Moses Lake
18	Mattawa
19	Ellensburg (Exact Location Uncertain)
20	Yakima
21	Sunnyside (Irrigation District Building)
22	Sunnyside (Airport)
23	Toppenish
24	Wastuchna
25	Walla Walla
26	McNary Dam
27	Baxter Substation

Figure A.55. Location of Nearby Community and Distant Community TLD Sampling Locations

Table A.2. Global Positioning Coordinates and Years of Data Collection at Offsite Upland TLD Sampling Locations

Name	Latitude	Longitude	Sampling Period (Years)	Page
Upland perimeter locations				
WPPSS 4 Warehouse	46.391573	-119.410924	1985–2005	A.38
1100 Area	46.323781	-119.287512	1978–1983	A.38
Battelle Complex	46.445889	-119.24998	1990–1995; 1999–2005	A.39
Richland Research Complex 63	46.339356	-119.274437	1973–1977	A.39
Richland Research Complex 64	46.345971	-119.276368	1973–1989	A.40
Richland Research Complex 65	46.350944	-119.283220	1973–1977	A.40
Richland Research Complex 66	46.351118	-119.279300	1973–1977	A.41
Richland Research Complex 67	46.351320	-119.272533	1973–1977	A.41
Horn Rapids Road, Mile 12	46.351482	-119.304311	1983–1990	A.42
Horn Rapids Substation	46.481704	-119.39146	1983–1990; 1998–2005	A.42
Prosser Barricade	46.340548	-119.269657	1973–1990; 1998–2005	A.43
Emergency Relocation Center (ALE)	46.391753	-119.535456	1971–1990	A.43
Rattlesnake Springs	46.512378	-119.681845	1971–1990; 1999–2005	A.44
Yakima Barricade	46.577978	-119.726094	1971–1990; 1998–2005	A.44
S End Vernita Bridge	46.63973	-119.732242	1971–1992 1999–2000	A.45
Vernita	46.639731	-119.732236	1971	A.45
Byers Landing	46.544968	-119.237245	1971–2005	A.46
Dogwood Met Tower	46.45362	-119.335205	1998–2005	A.46
Ringold Area			1971–1975	A.47
Ringold Met. Tower	46.358583	-119.247651	1983–2005	A.47
WPPSS Fir Road (No. 8)	NA	NA	1985–1997	A.48
W. End Fir Road	46.340423	-119.282326	1977–1990; 1997–2005	A.48
Wahluke Slope	46.736887	-119.640927	1971–1990; 1998–2005	A.49
Wahluke Slope Control Plot 17	46.6656919	-119.6845108	1971–1977	A.49
Wahluke Slope Control Plot 18	46.73457215	-119.561405	1971–1977	A.49
Wahluke Slope Control Plot 19	46.73530976	-119.5348799	1971–1977	A.49
Wahluke Slope Control Plot 20	46.73691636	-119.4871899	1971–1977	A.49
Wahluke Slope Control Plot 21	46.73548849	-119.4277939	1971–1977	A.49
Wahluke Slope Control Plot 22	46.68525337	-119.4090471	1971–1977	A.49
Wahluke Slope Control Plot 23	46.61651943	120.6935823	1971–1977	A.49
Wahluke Slope Control Plot 24	46.61276211	-119.3845452	1971–1977	A.49

Table A.2. (contd)

Name	Latitude	Longitude	Sampling Period (Years)	Page
Wahluke Slope Control Plot 46 (Hanford 46 in earlier years)	46.59396218	-119.3728491	1971–1977	A.49
Nearby Communities				
Benton City	46.275718	-119.499132	1971–2005	A.50
Prosser	46.206661	-119.752825	1986–1990	A.50
Richland (700 Area 747 Building)	46.27692	-119.280329	1971–1991	A.51
Leslie Groves Park (Richland)	46.314976	-119.255649	1991–2001	A.51
Kennewick	46.193121	-119.158895	1971–1973; 1986–2005	A.52
Pasco (BPA location)	46.257277	-119.098129	1971–1994	A.52
Pasco (CBC Location)	46.251686	-119.119467	1994–2005	A.53
Basin City School	46.594756	-119.153922	1990–2005	A.53
Edwin Markham School	46.430581	-119.196728	1990–2005	A.54
Eltopia	46.458983	-119.023615	1971–1974; 1986–1991	A.54
Cooke Brothers Farm	46.529813	-119.118223	1971–1982	A.55
Pettett Farm	46.398186	-119.248344	1977–1990	A.55
Wahluke Water Master	46.674826	-119.17334	1971–1982	A.56
Othello	46.827833	-119.16328	1971–1991; 1995–2005	A.56
Connell	46.663245	-118.868014	1971–1991	A.57
Berg Ranch	46.738770	-119.34566	1971–1990	A.57
Moses Lake	47.129609	-119.268288	1971–1991	A.58
Mattawa	46.736233	-119.896931	1986–2005	A.58
Distant Communities				
Ellensburg	NA	NA	1971–1974	A.59
Yakima	46.570377	120.542123	1996–2005	A.59
Sunnyside (Irrigation District Building)	46.326739	-120.003725	1971–1984	A.60
Sunnyside (Airport)	46.326164	-119.972815	1985–1994	A.60
Toppenish	46.374044	120.393103	1995–2005	A.61
Wastucna	46.751514	-118.314483	1971–1990	A.61
Walla Walla	46.688251	-118.28269	1971–1990	A.62
McNary Dam	45.924891	-119.26243	1971–1990	A.62

ALE = Fitzner/Eberhardt Arid Lands Ecology Reserve.
BPA = Bonneville Power Administration.
CBC = Columbia Basin College.
WPPSS = Washington Public Power Supply System.

A.3.1 TLD Results at Perimeter Locations

This section contains plots of TLD data for upland TLD sampling locations that occurred on the Hanford Site perimeter and locations adjacent to the perimeter (Figures A.56 through A.79).

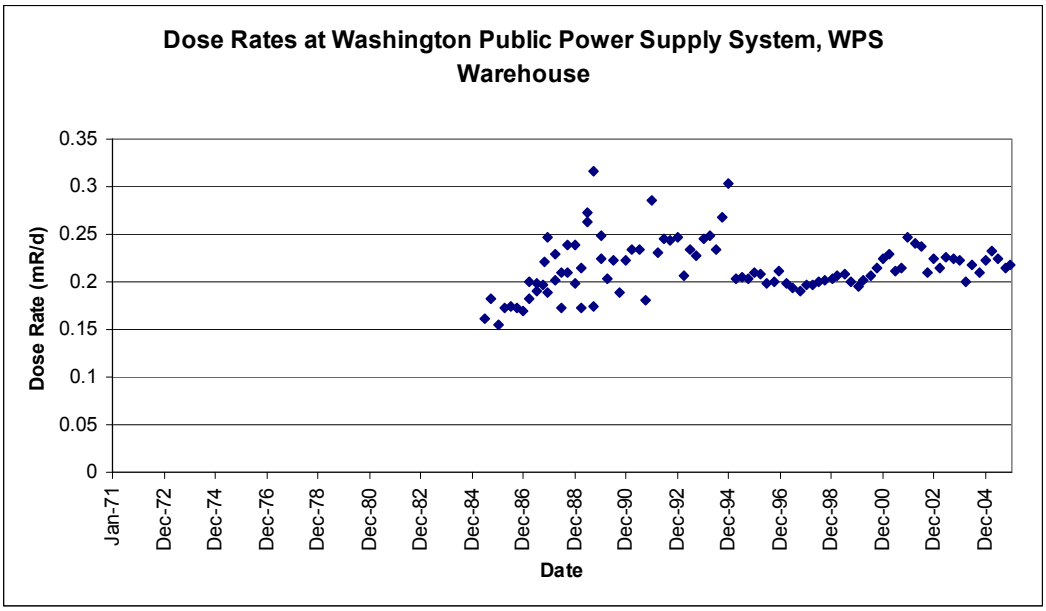


Figure A.56. Dose Rates Were Measured at the WPPSS (presently Energy Northwest; WPS in figure title is truncated for HEIS formatting limitations) Warehouse from March 1985 Through December 2005. The dosimeter was located on the northeast corner of the fence of the old WPPSS warehouse located off of George Washington Way in northern Richland.

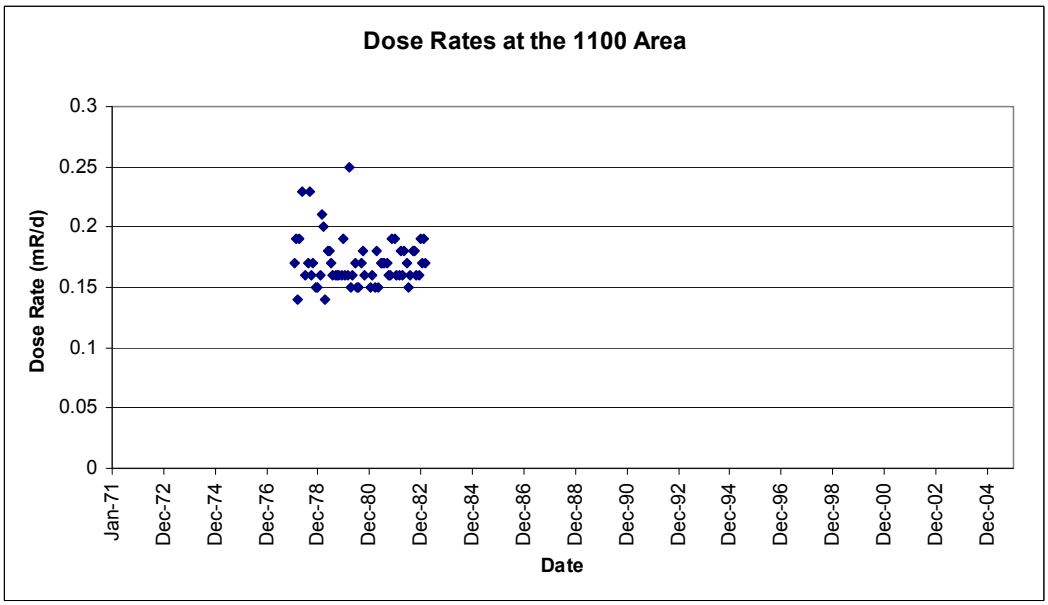


Figure A.57. Dose Rates Were Measured at the 1100 Area from January 1978 Through February 1983. The dosimeter was located west of Stevens Drive and the old bus parking lot, near a small scale house near the main railroad tracks.

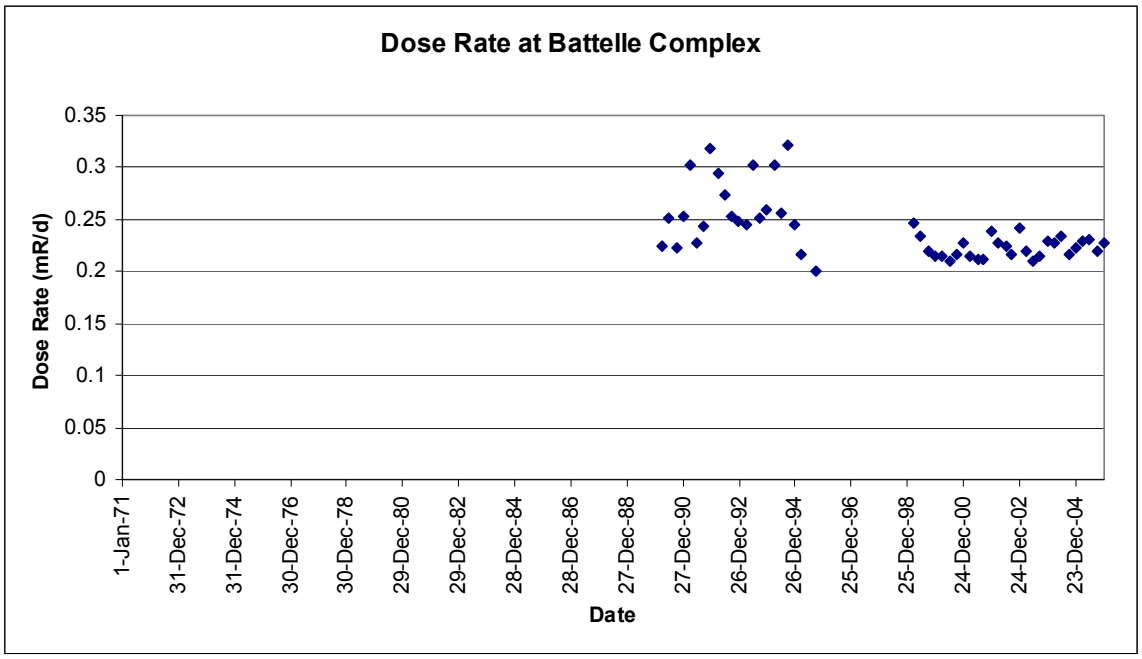


Figure A.58. Dose Rates Were Measured at the Battelle Complex from January 1990 Through September 1995, Then Restarted in January 1999 and Continued Through December 2005. The dosimeter was located south of the Battelle tennis courts and softball field out from right field of the softball diamond.

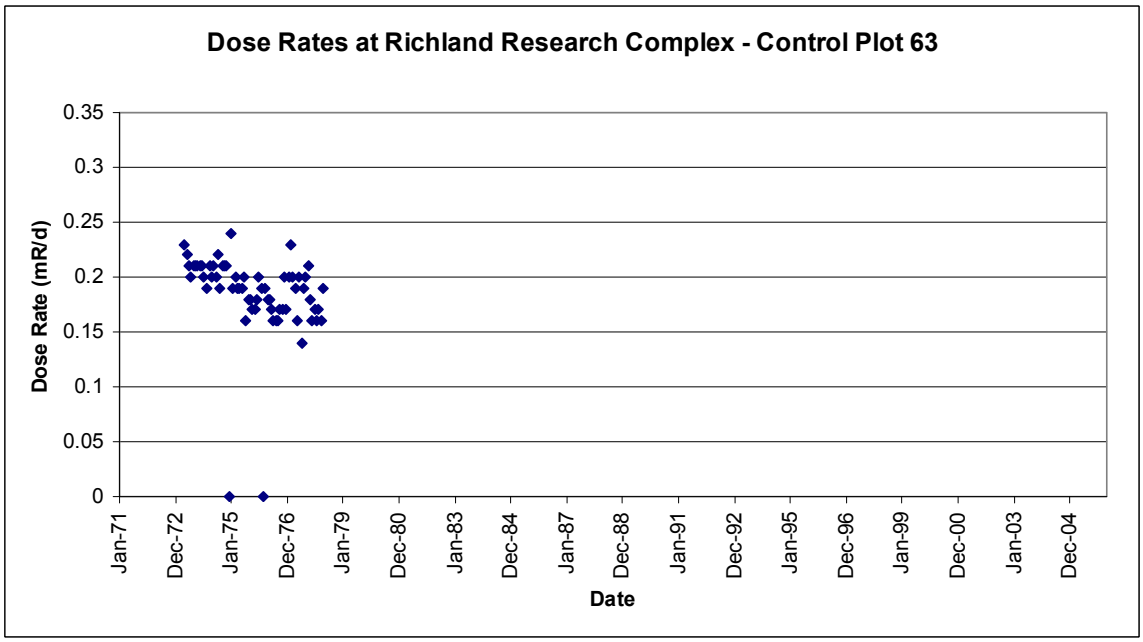


Figure A.59. Dose Rates Were Measured at the Richland Research Complex Control Plot 63 from April 1973 Through December 1977

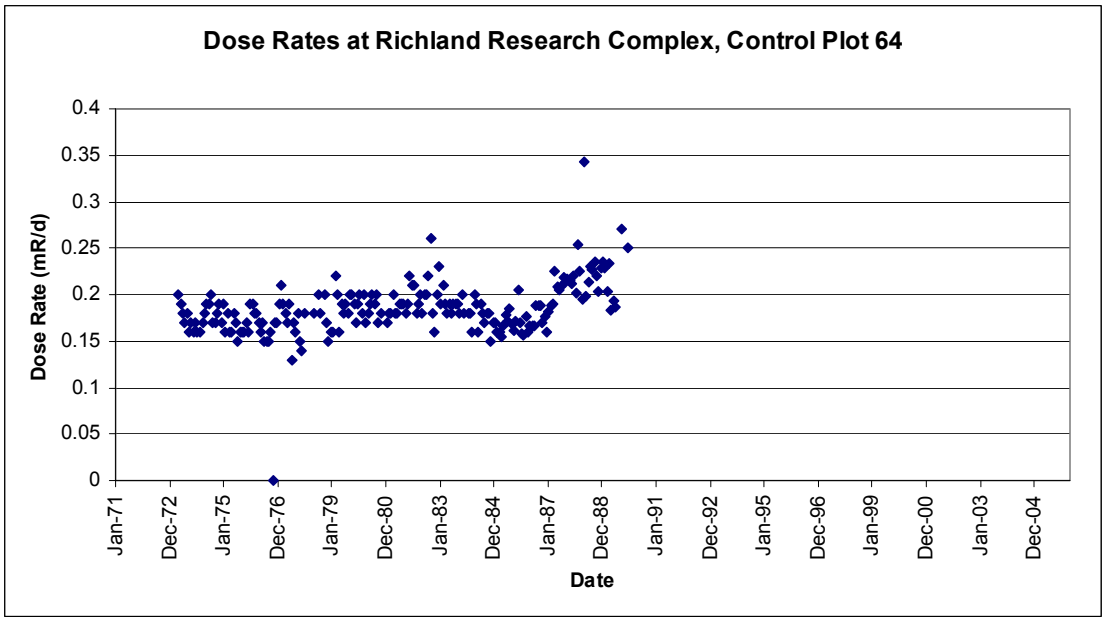


Figure A.60. Dose Rates Were Measured at the Richland Research Complex Control Plot 64 from April 1973 Through December 1989

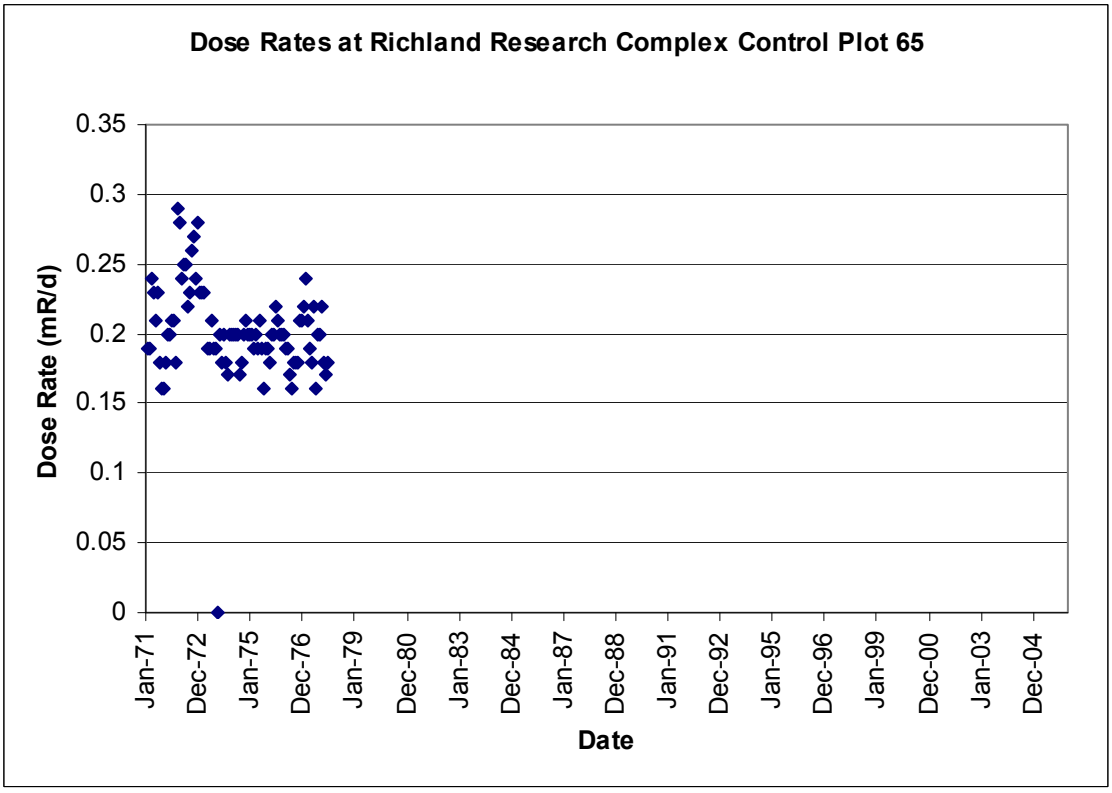


Figure A.61. Dose Rates Were Measured at the Richland Research Complex Control Plot 65 from January 1971 Through December 1977

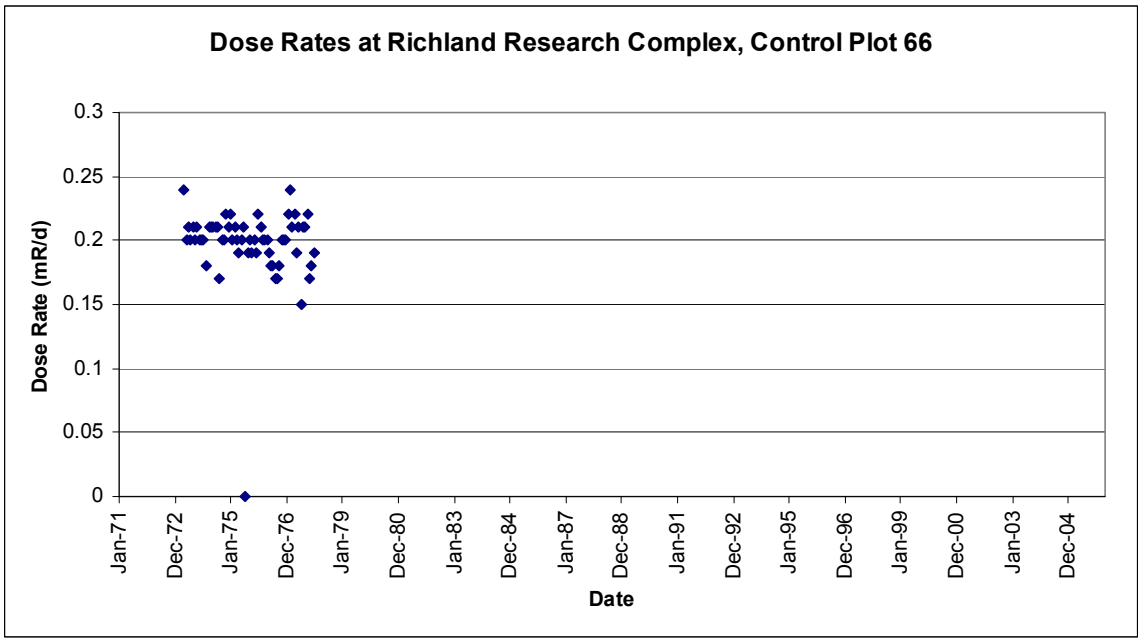


Figure A.62. Dose Rates Were Measured at the Richland Research Complex Control Plot 66 from April 1973 Through December 1977

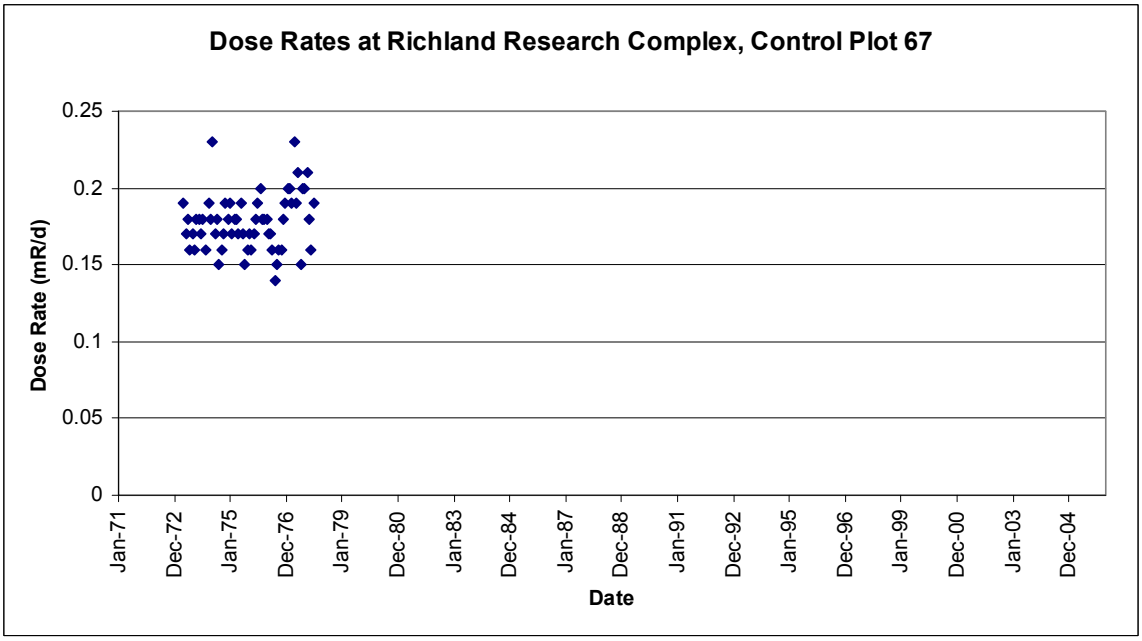


Figure A.63. Dose Rates Were Measured at the Richland Research Complex Control Plot 67 from April 1973 Through December 1977

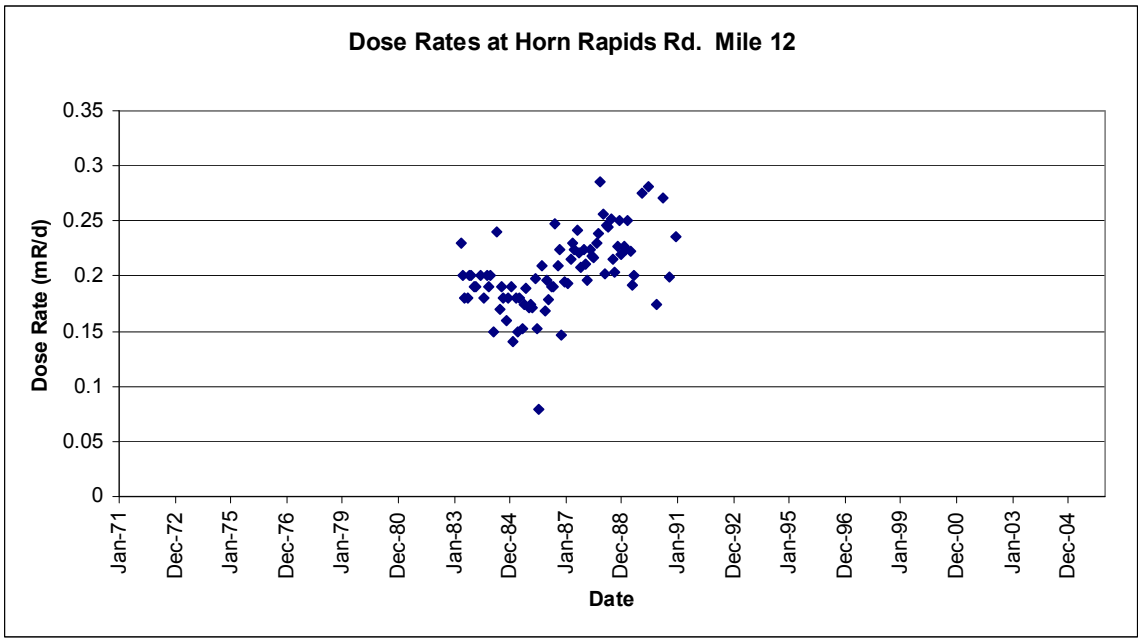


Figure A.64. Dose Rates Were Measured at Horn Rapids Road Mile 12 from March 1983 Through December 1990

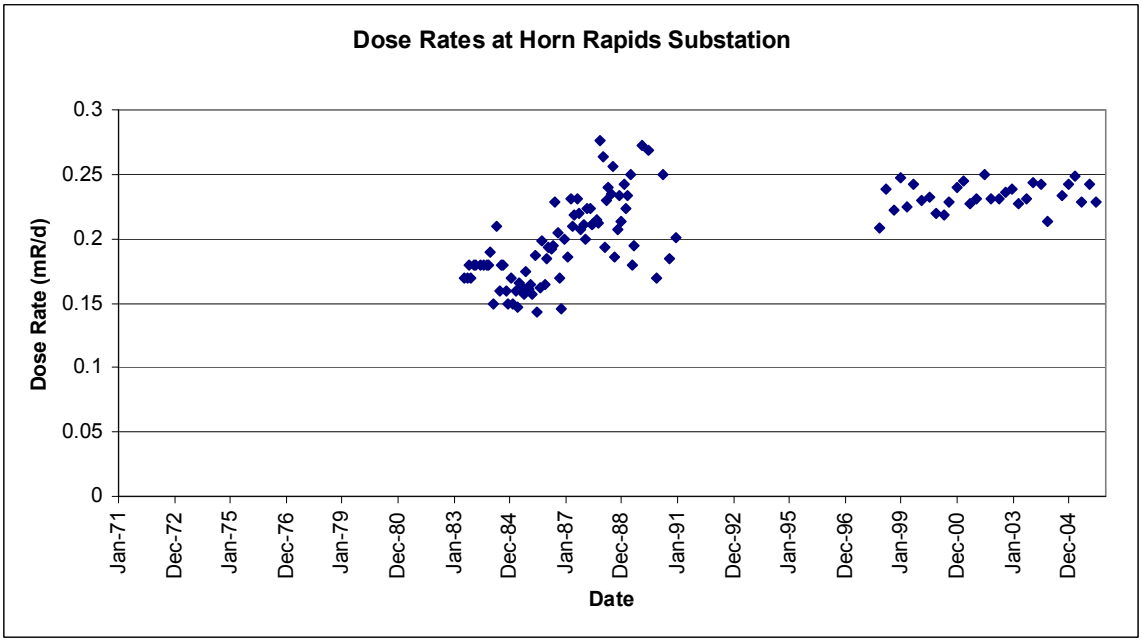


Figure A.65. Dose Rates Were Measured at the Horn Rapids Substation from May 1983 Through December 1990, Then Restarted in the First Quarter of 1998 and Continued Through December 2005. The dosimeter was located at the Horn Rapids Substation approximately 4.2 miles from the intersection of Stevens Drive and Horn Rapids Road. The posting on the substation is White Bluffs Substation; it was called Horn Rapids substation because of its location on Horn Rapids Road and proximity to Horn Rapids Dam.

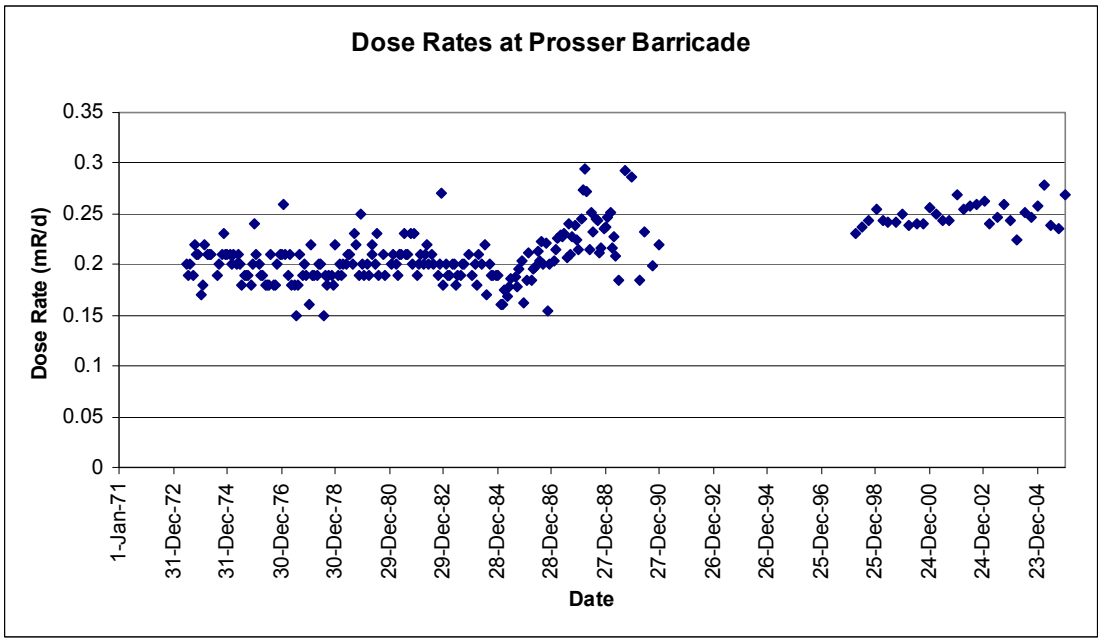


Figure A.66. Dose Rates Were Measured at the Prosser Barricade from June 1973 Through December 1990, Then Restarted in January 1998 and Continued Through December 2005. The dosimeter was located approximately 0.9 mile north of intersection of Highway 240 and Route 10.

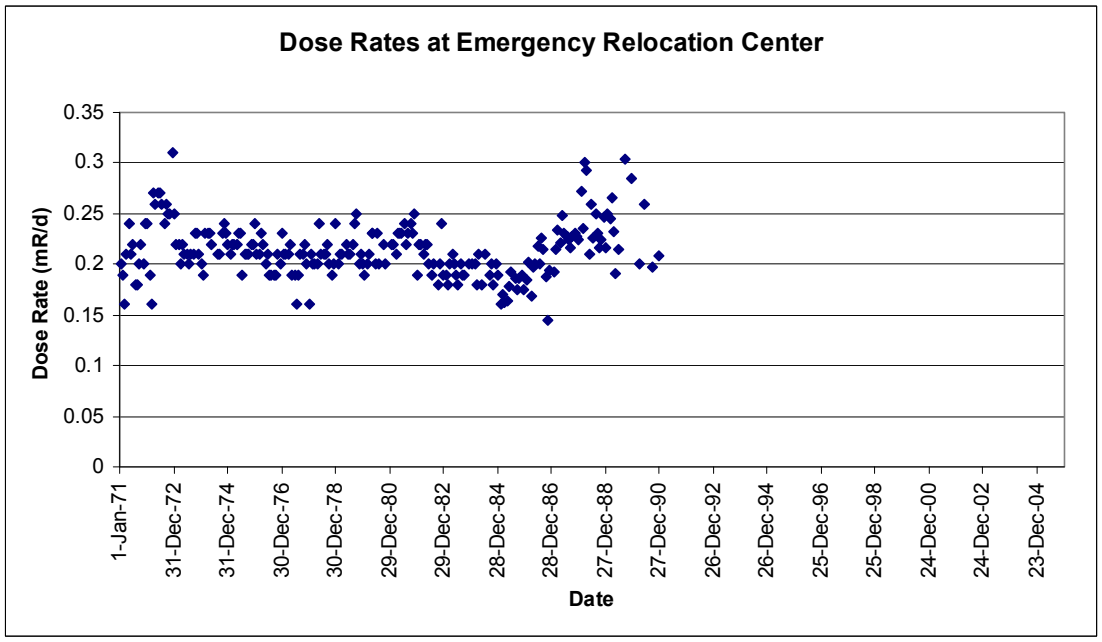


Figure A.67. Dose Rates Were Measured at the Emergency Relocation Center from January 1971 Through December 1990. The dosimeter was located on the Fitzner/Eberhart Arid Land Ecology (ALE) Reserve, near the ALE Field Laboratory. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

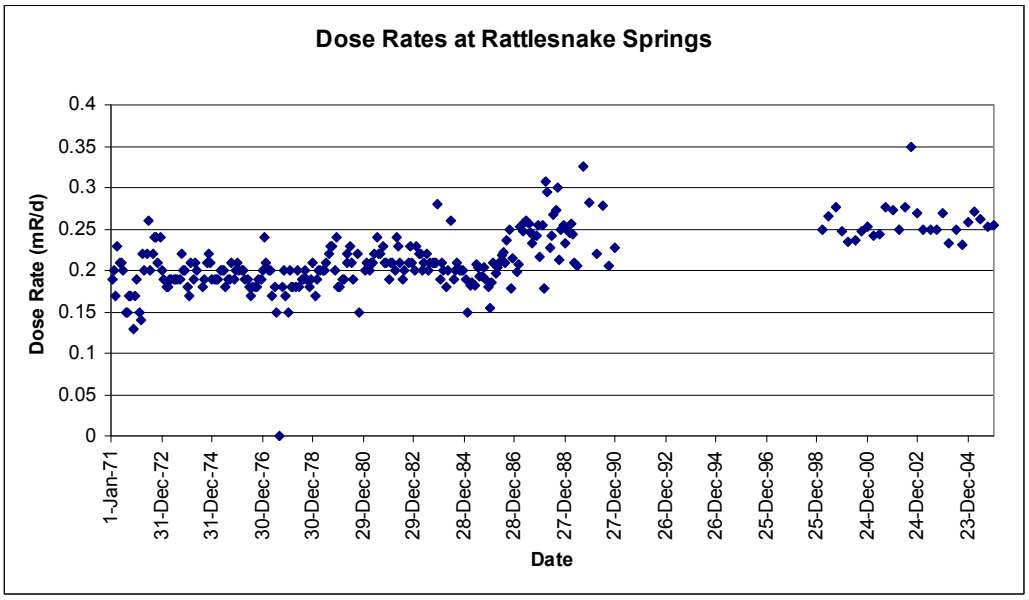


Figure A.68. Dose Rates Were Measured at Rattlesnake Springs from January 1971 Through December 1990, Then Restarted in the First Quarter of 1999 and Continued Through December 2005. The dosimeter was located approximately 0.6 mile west of Highway 240 after entering the Arid Land Ecology Reserve through Gate 118.

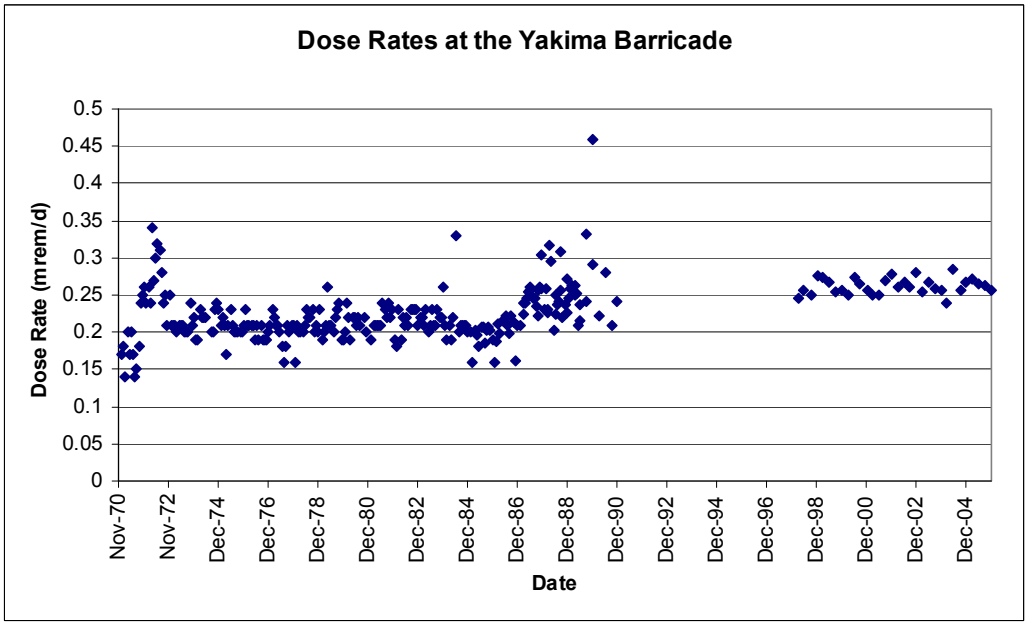


Figure A.69. Dose Rates Were Measured at the Yakima Barricade from January 1971 Through December 1990, Then Resumed in First Quarter of 1998 and Continued Through December 2005. The dosimeter was located just north of the Yakima Barricade off Route 11 A. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973). The elevated dose rate (TLD-700) reported in December 1989 was not mentioned in the Hanford Site Environmental Report (Jaquish and Bryce 1990) because that assessment was based on the TLD-400 design.

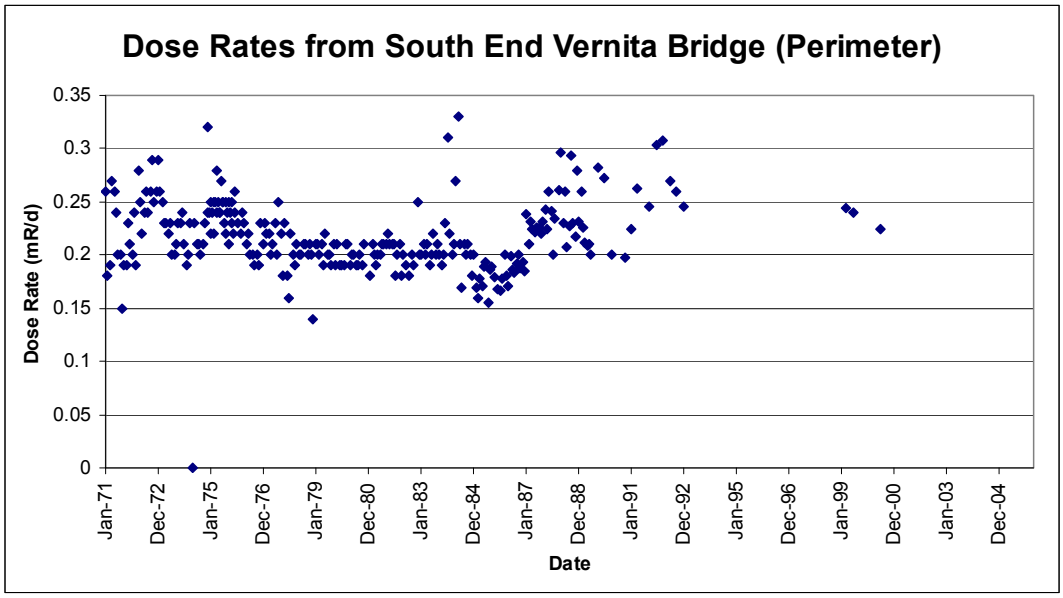


Figure A.70. Dose Rates Were Measured at the South End of Vernita Bridge from 1971 Through 1992. Measurements resumed in 1999, but due to continued vandalism of the dosimeter, the location was moved to the shoreline of the Columbia River and was re-classified as shoreline.

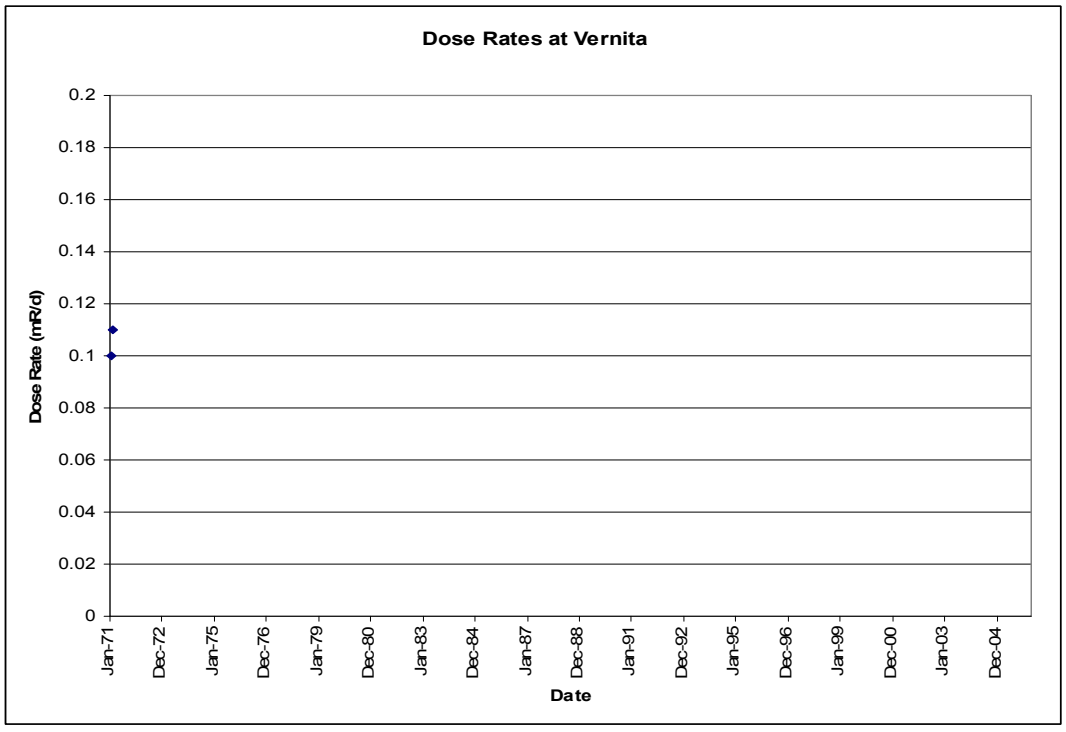


Figure A.71. Dose Rates Were Measured at the Vernita Location for Two Months in 1971

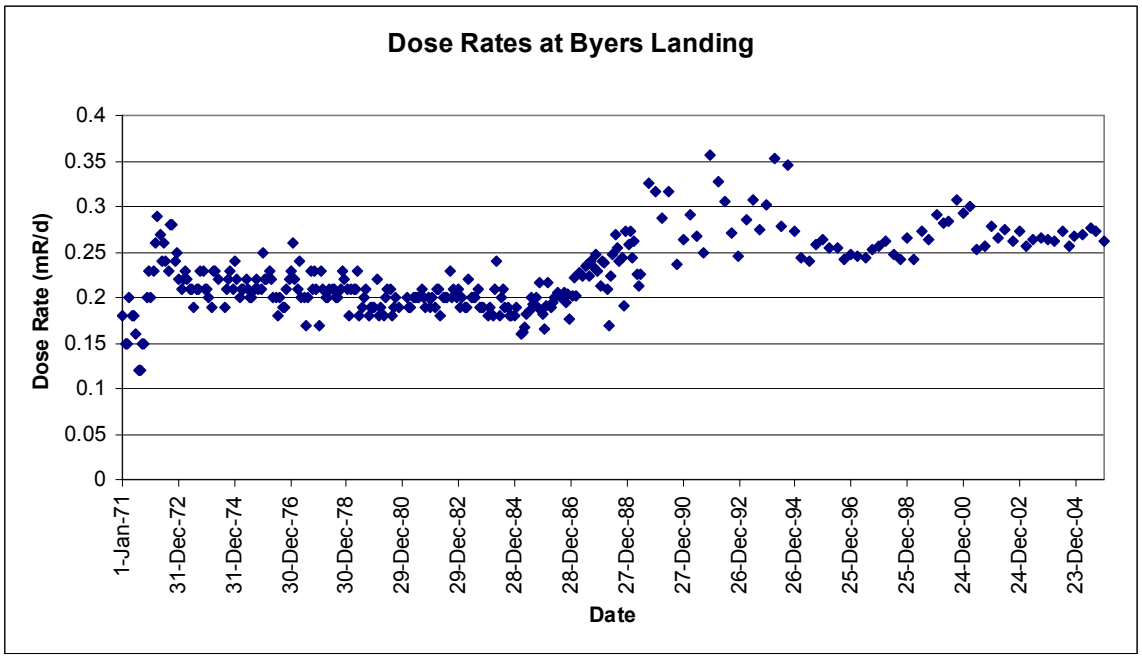


Figure A.72. Dose Rates Were Measured at Byer's Landing from January 1971 Through December 2005. The dosimeter was located off Road 68 near the Esquatzel Diversion canal, about one-half mile east of the bridge across the canal on the north side of canal. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

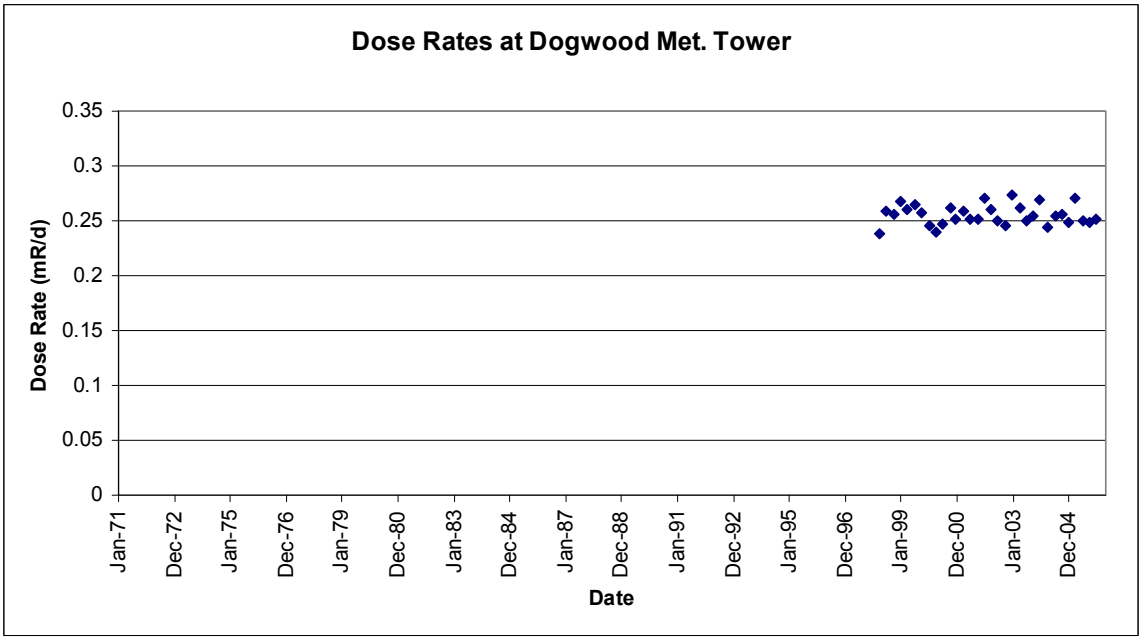


Figure A.73. Dose Rates Were Measured at the Dogwood Meteorology Tower from January 1998 Through December 2005. The dosimeter was located at the west end of Dogwood Road near its intersection with Cottonwood Drive.

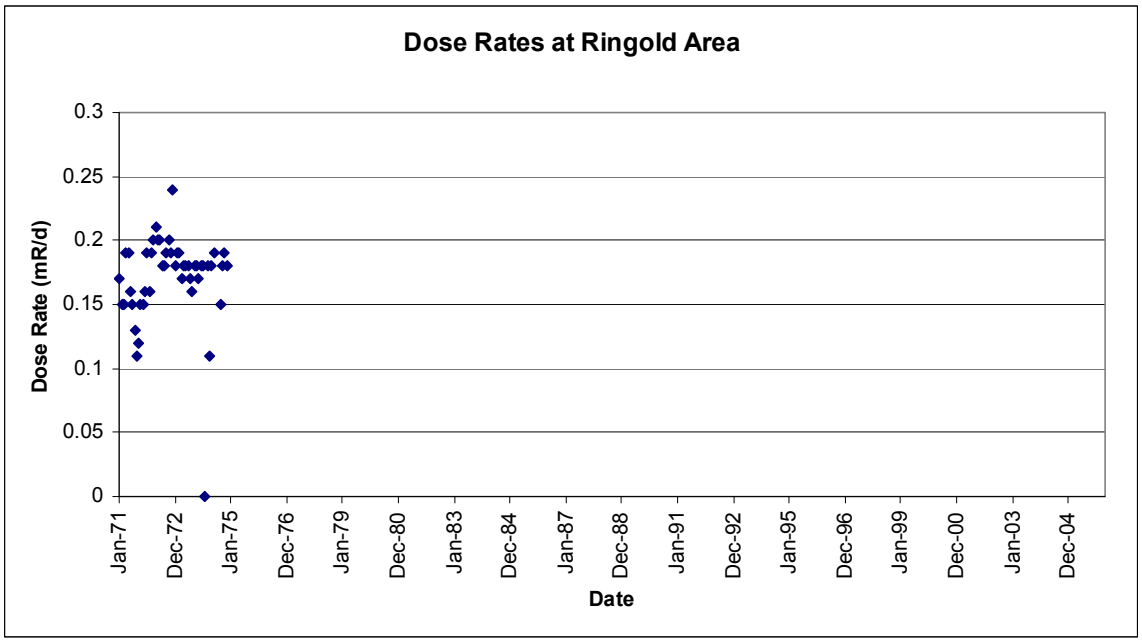


Figure A.74. Dose Rates Were Measured at Ringold from January 1971 Through November 1974. GPS coordinates were not determined for this location.

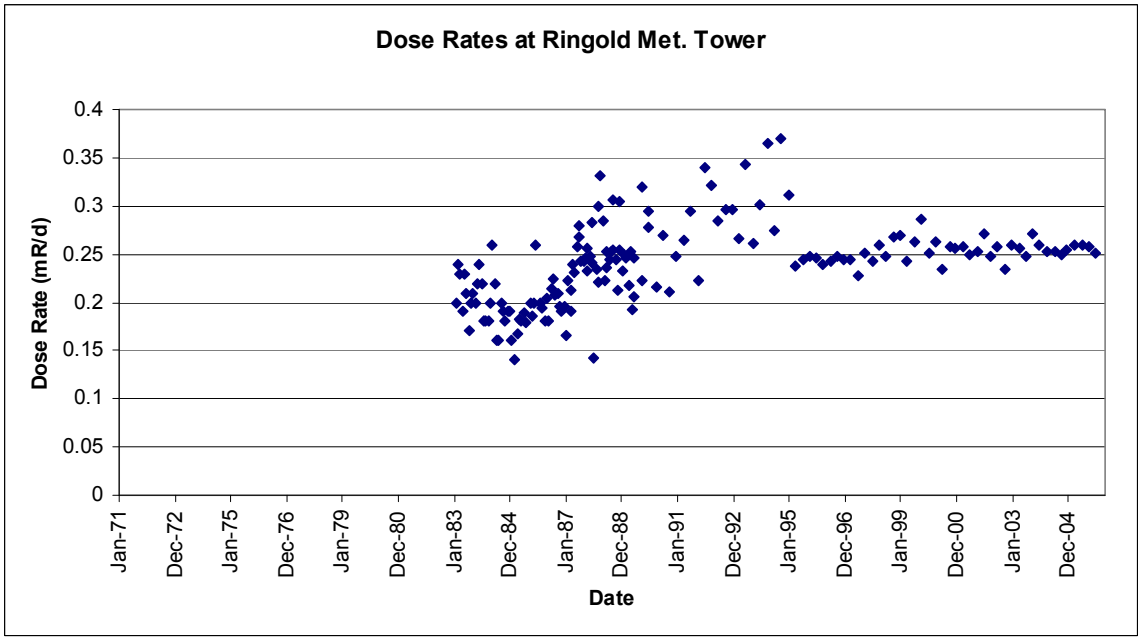


Figure A.75. Dose Rates Were Measured at the Ringold Meteorology Tower from December 1982 Through December 2005

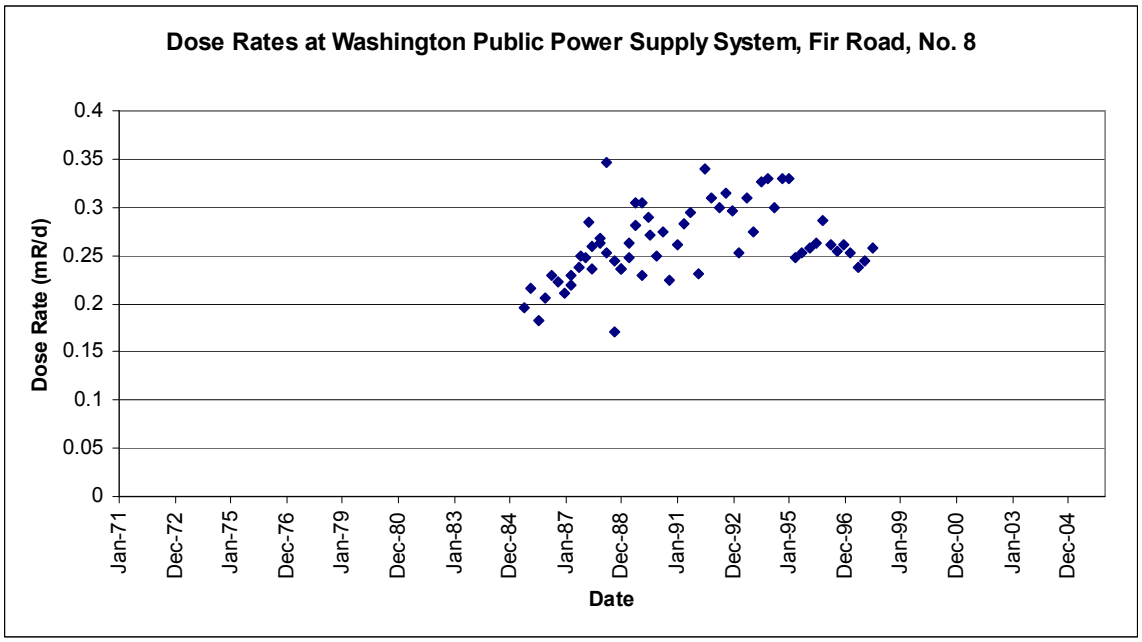


Figure A.76. Dose Rates Were Measured at WPPSS, Fir Road from April 1985 Through December 1997 and Included Both TLD-400 (April 1985–December 1989) and TLD 700 (December 1986 Through September 1997) Dosimeters. This location and the following west of Fir Road location are essentially the same location. Over the years, the location was moved to accommodate farming operations at the site.

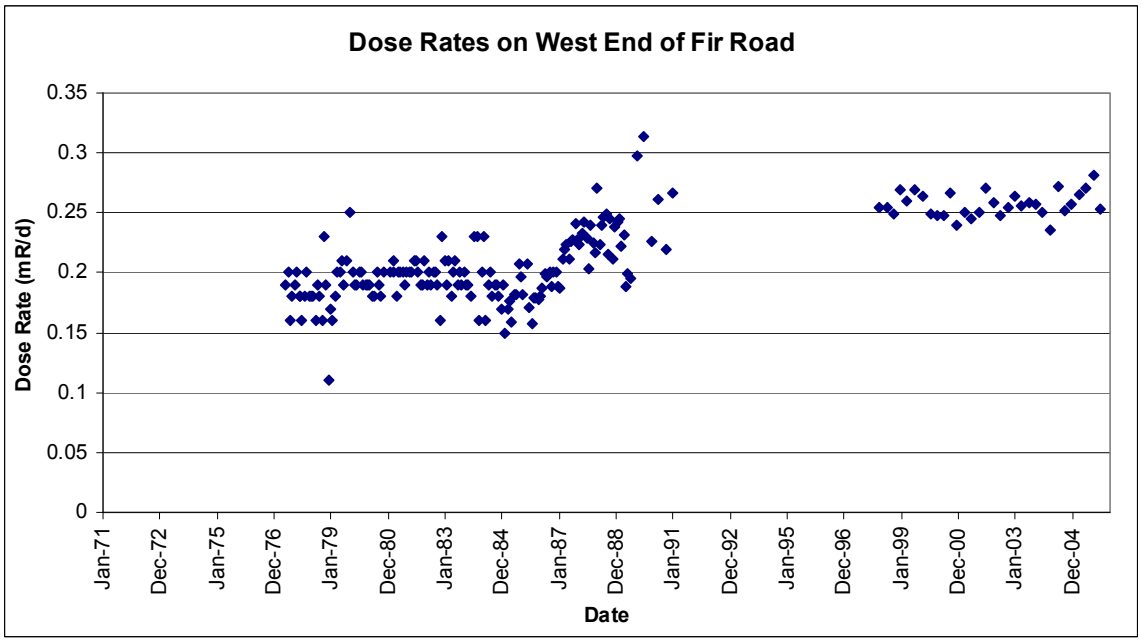


Figure A.77. Dose Rates Were Measured at the West End of Fir Road from 1977 Through 1990 and Then Were Resumed Again in 1998 and Continued Through 2005

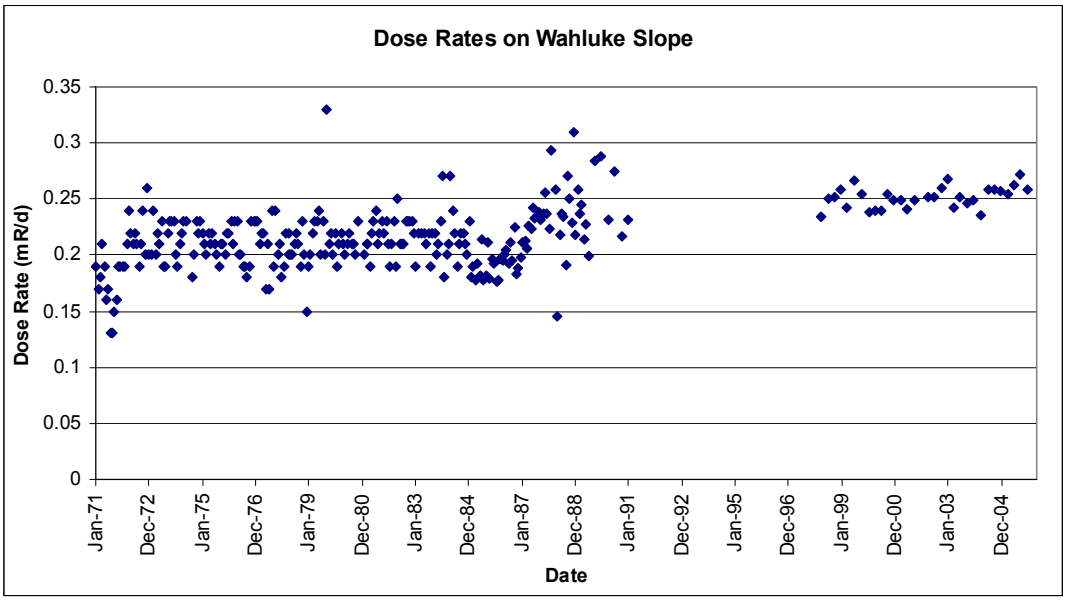


Figure A.78. Dose Rates Were Measured at Wahluke Slope from January 1971 Through December 1990 and Were Restarted in the First Quarter of 1998 and Continued Until December 2005. The dosimeter was located near the intersection of Road 24 SW and Road G SW.

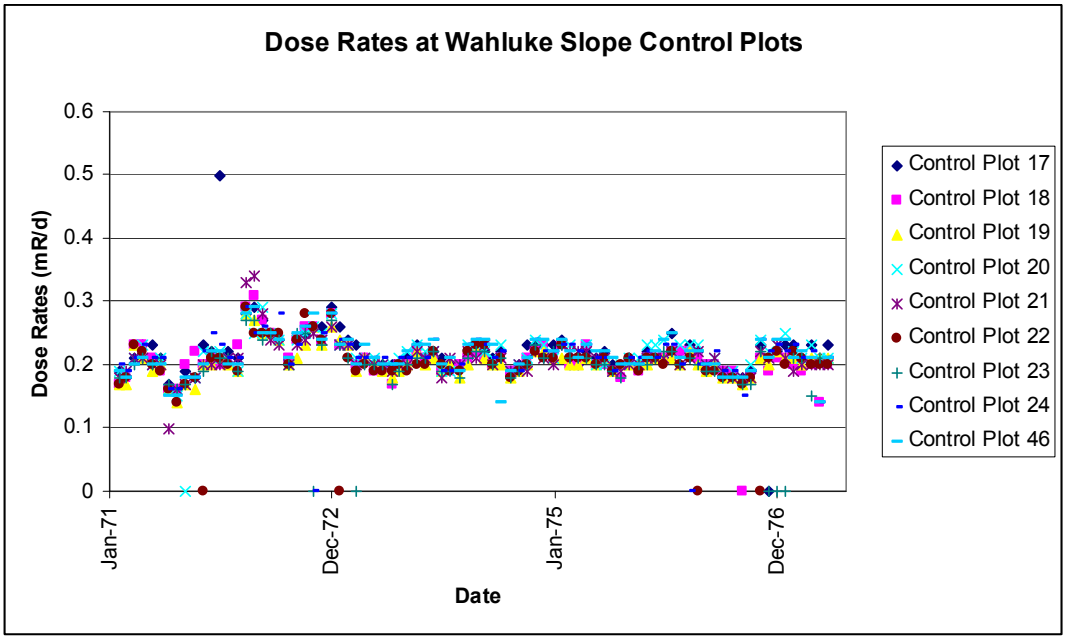


Figure A.79. Dose Rates Were Measured Monthly at Wahluke Control Plots 17, 18, 19, 20, 21, 22, 23, 24, and 46 from January 1971 Through June 1977. Fallout from Chinese weapons tests were detected in 1972. No mention was found in either the 1971 annual surveillance report (Bramson and Corley 1972a) or in the annual status report (Bramson and Corley 1972b) regarding the elevated dose rate measure at Wahluke Control Plot 17 in December 1971. The measurements of external dose rates at these locations complemented soil and vegetation sampling that was conducted to address the release of Wahluke Slope land for unrestricted public use. A map of locations is found in Wooldrige (1968, p. 50); the stations may have been established in 1967.

A.3.2 Nearby Community TLD Locations

This section contains plots of TLD data for upland TLD sampling locations designated as Nearby Communities (Figures A.80 through A.97).

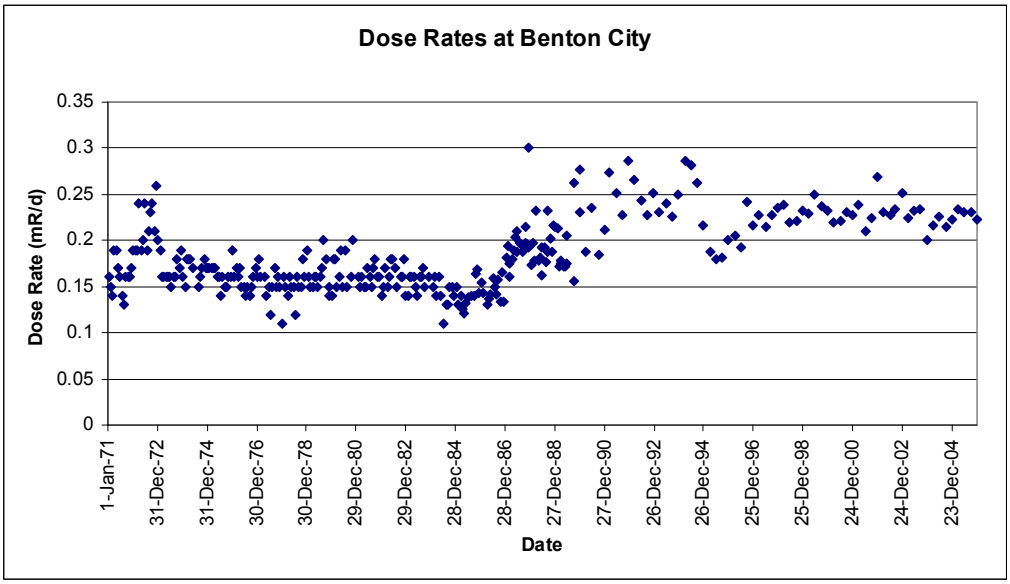


Figure A.80. Dose Rates Were Measured in Benton City from January 1971 Through December 2005. The dosimeter was located south of the Kiona-Benton High School on school property. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973). The highest dose rate was measured by a TLD-700 during the last quarter of 1987. In the 1970s, Benton City was considered part of the perimeter network.

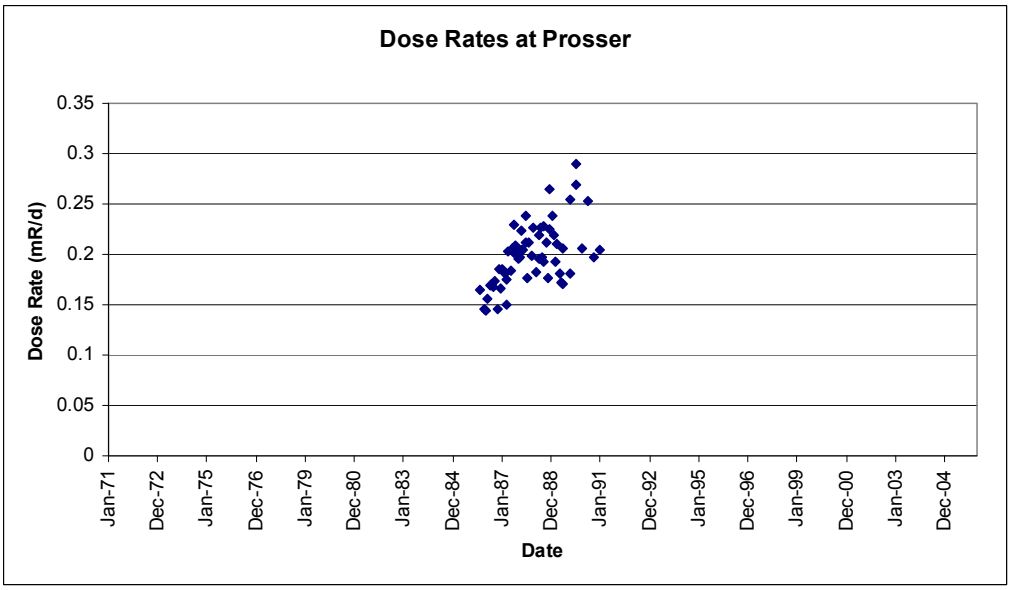


Figure A.81. Dose Rates Were Measured at Prosser from January 1986 Through December 1990. From January 1987 through December 1989, two dosimeter types were deployed at Prosser.

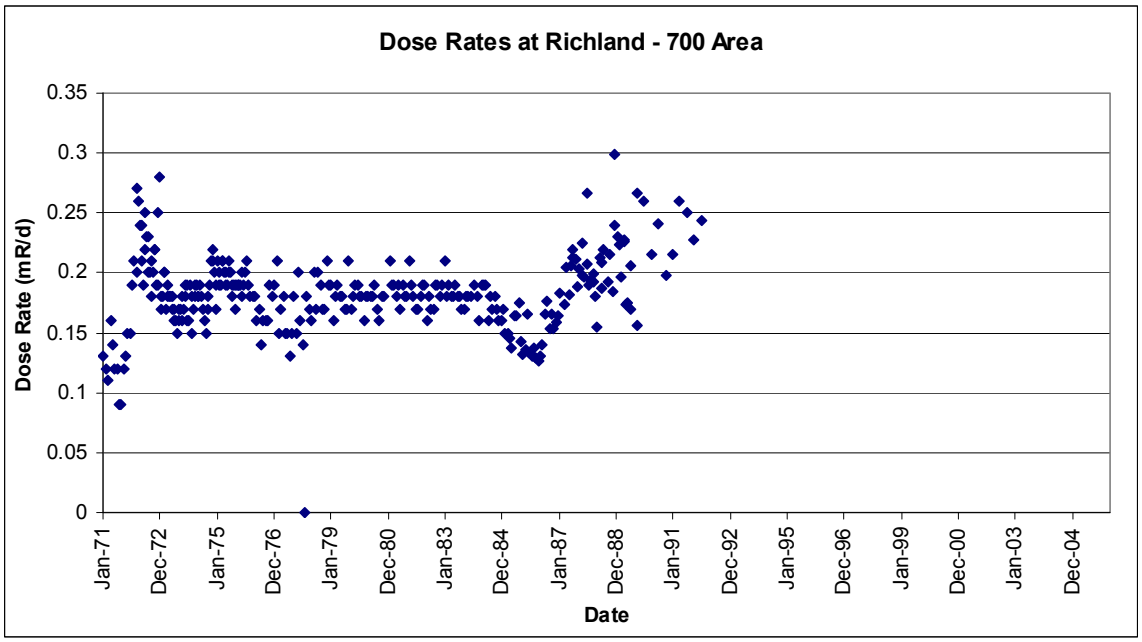


Figure A.82. Dose Rates Were Measured at Richland from January 1971 Through December 1991. This TLD was located adjacent to the whole body counting room (747 Building) at the corner of Knight and Goethals.

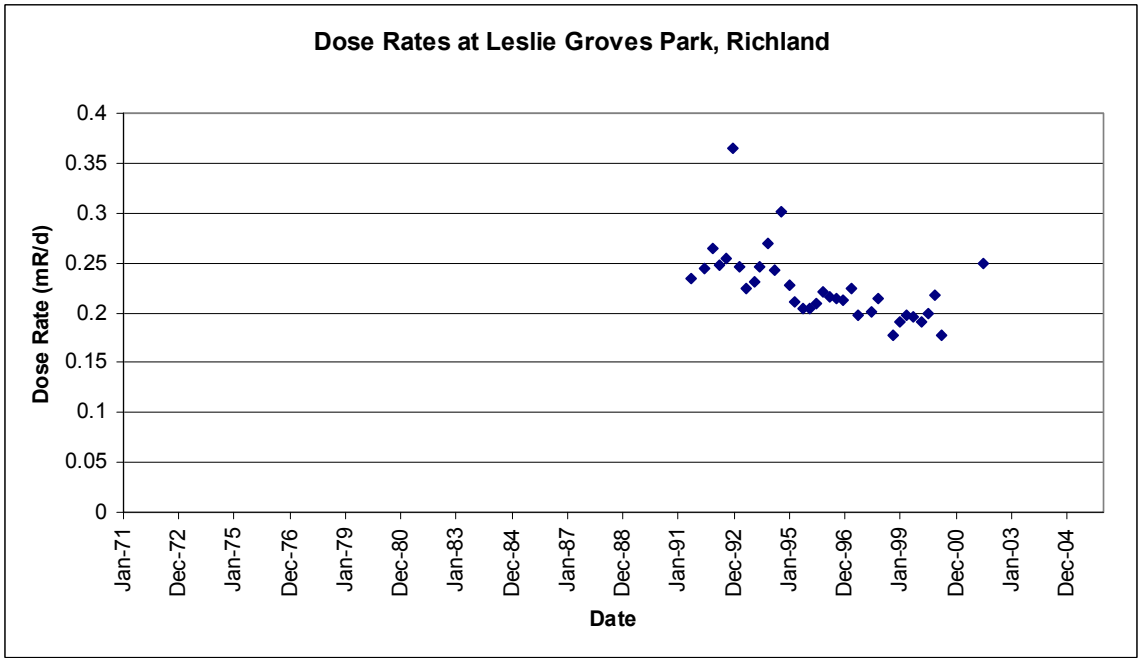


Figure A.83. Dose Rates Were Measured at Leslie Groves Park in Richland from April 1991 Through December 2001. The dosimeter was originally located at the community monitoring station at the north end of Leslie Groves Park, but was moved closer to the Columbia River shoreline in May 2000 due to vandalism at the monitoring station. Continued vandalism prompted the discontinuation of this dosimeter location and the dosimeter was relocated upstream to private property and re-named N. Richland and reclassified as shoreline.

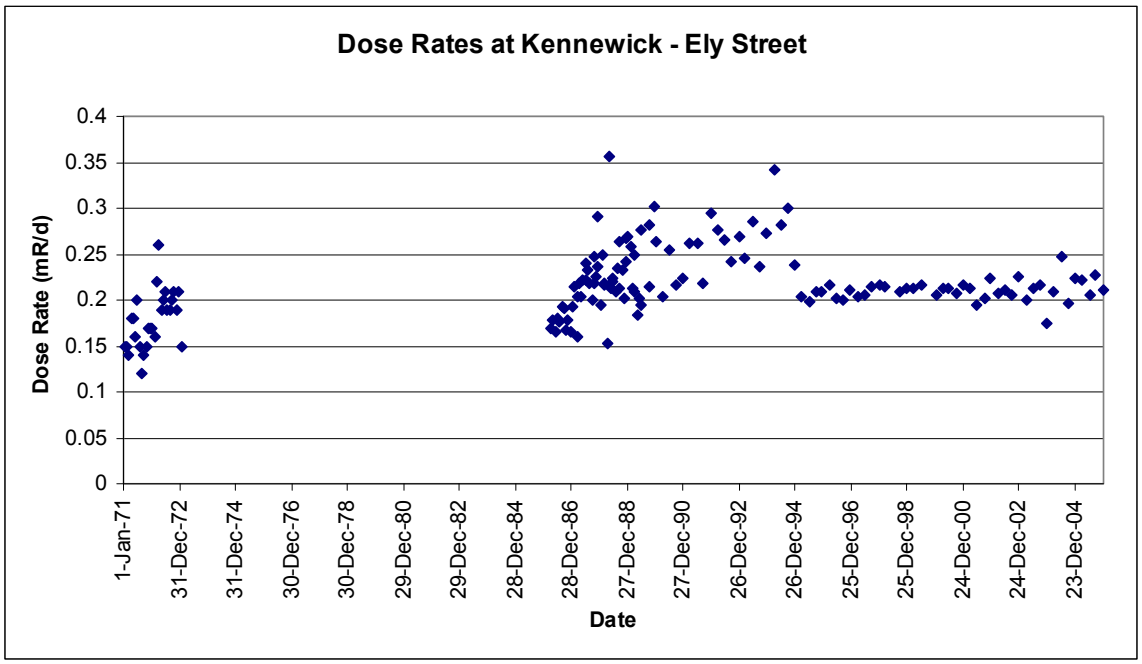


Figure A.84. Dose Rates Were Measured in Kennewick on Ely Street from January 1971 Through February 1973, Then Resumed in February 1986 and Continued Through December 2005. The dosimeter was located on the fence of the County Road Department on Ely Street.

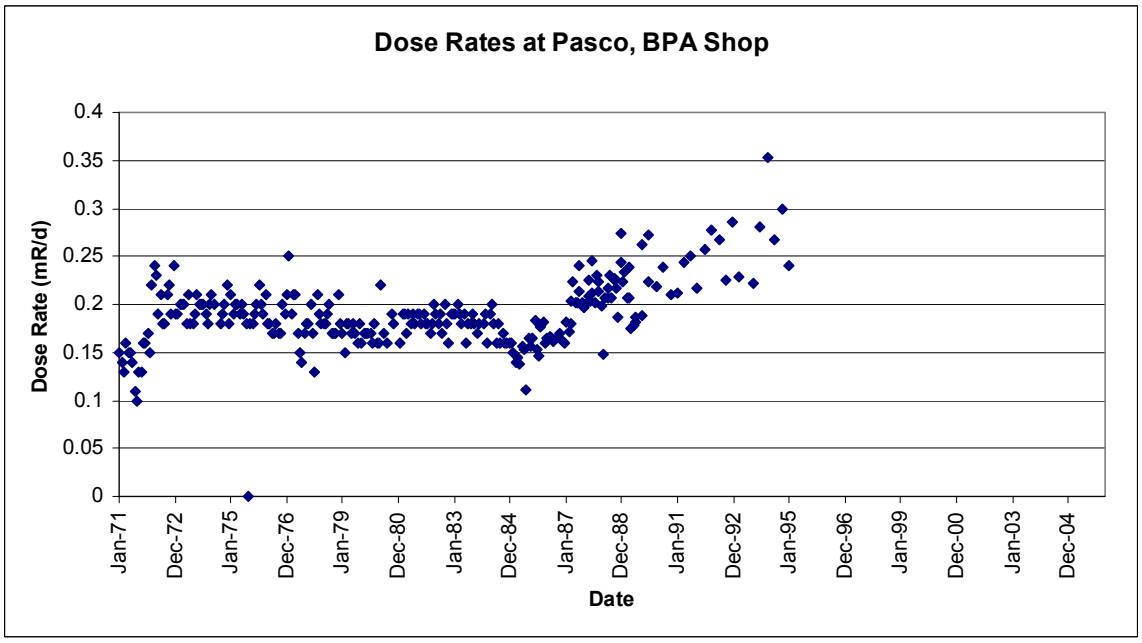


Figure A.85. Dose Rates Were Measured at Pasco from January 1971 Through December 1994. The dosimeter was originally located at the Bonneville Power Administration maintenance shop off of 4th Avenue, but was repositioned to the Columbia Basin Community College campus in December 1994. In the 1970s, Pasco was considered to be part of the perimeter network.

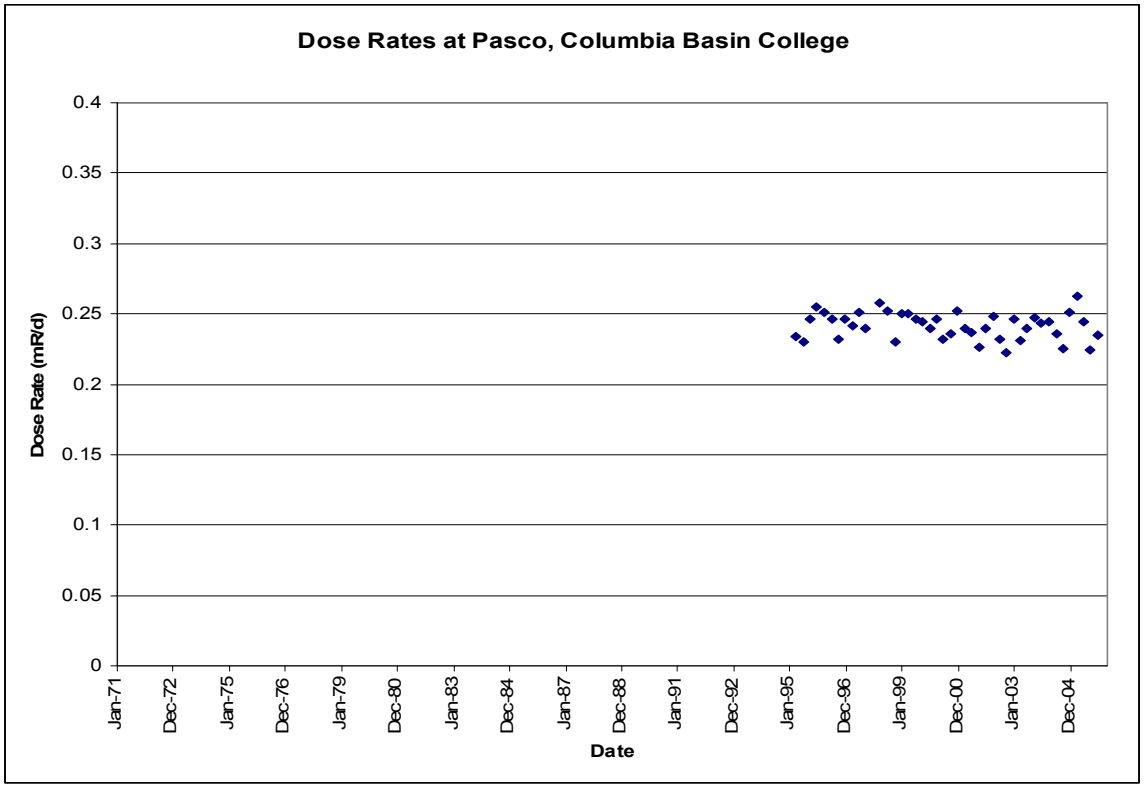


Figure A.86. Dose Rates Were Measured at the Pasco Columbia Basin College Location from January 1995 Through December 2005

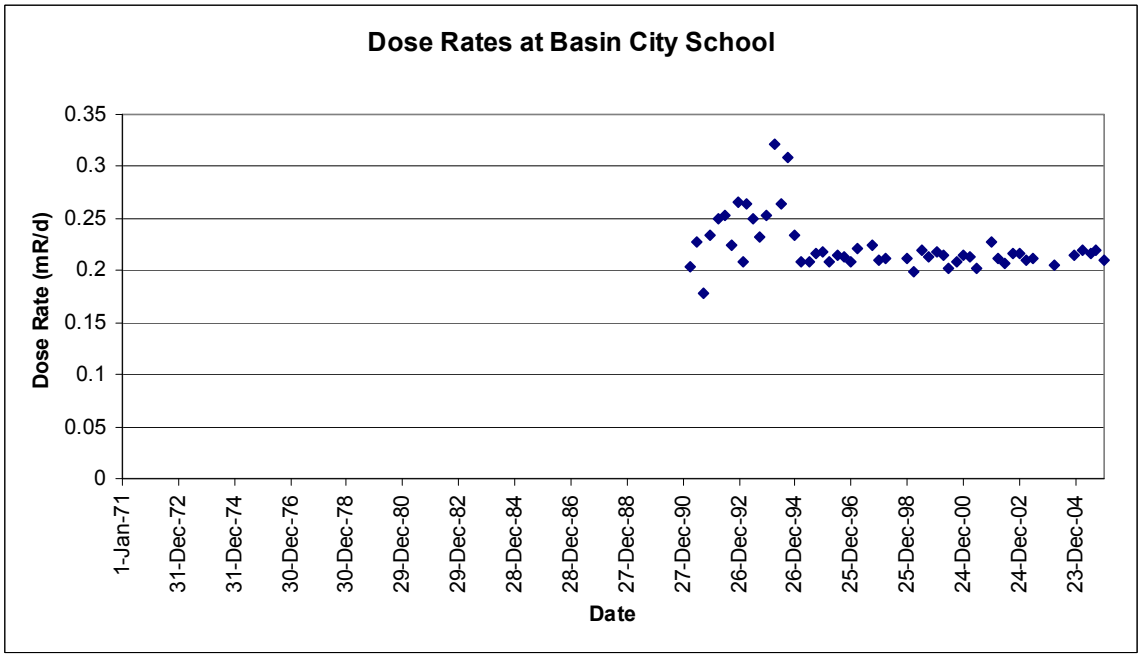


Figure A.87. Dose Rates Were Measured at the Basin City School from March 1991 Through December 2005

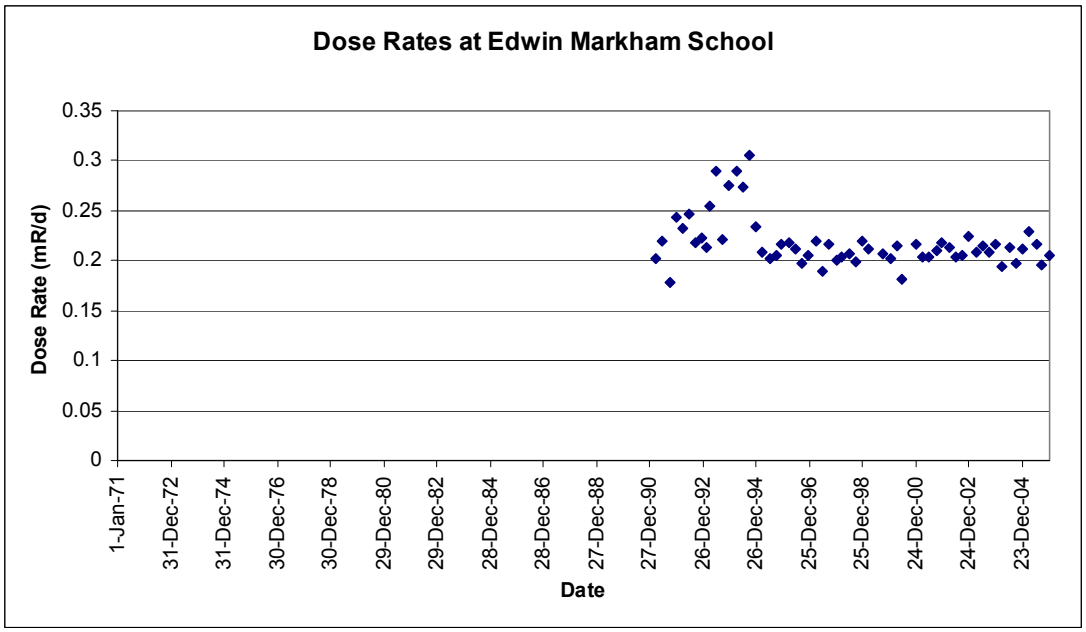


Figure A.88. Dose Rates Were Measured at the Edwin Markham School from March 1991 Through December 2005. The dosimeter was located at the community monitoring station on school property near the intersection of Taylor Flats Road and Elm Street.

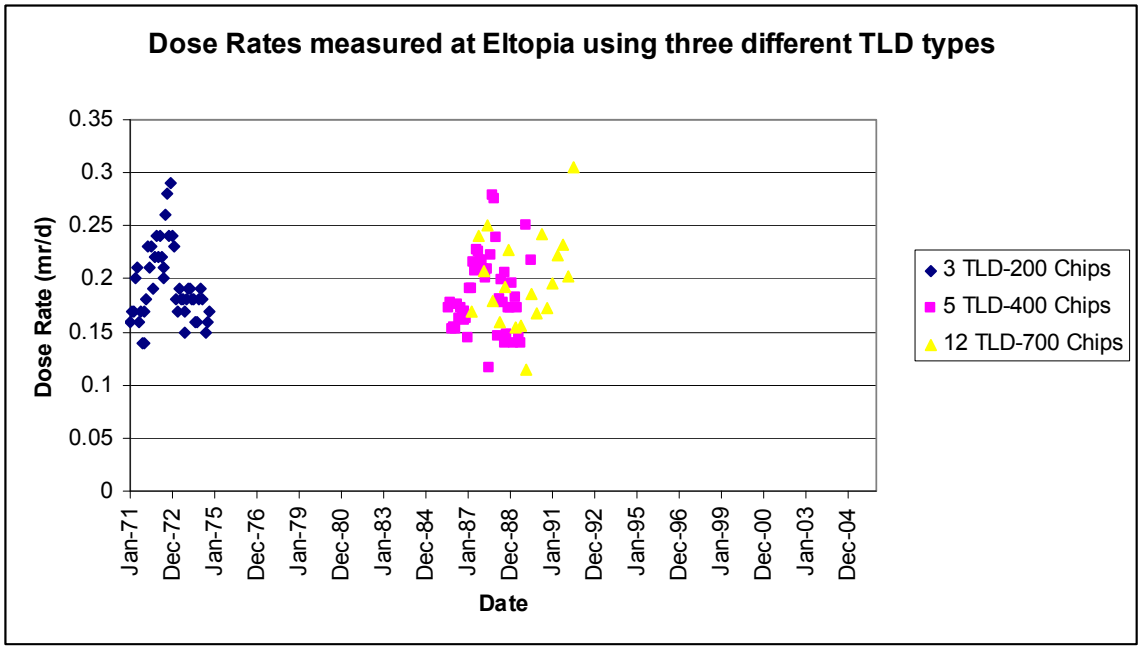


Figure A.89. Dose Rates Were Measured at Eltopia from January 1971 Through October 1974 and Then Re-Started in January 1986 and Continued through December 1991. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

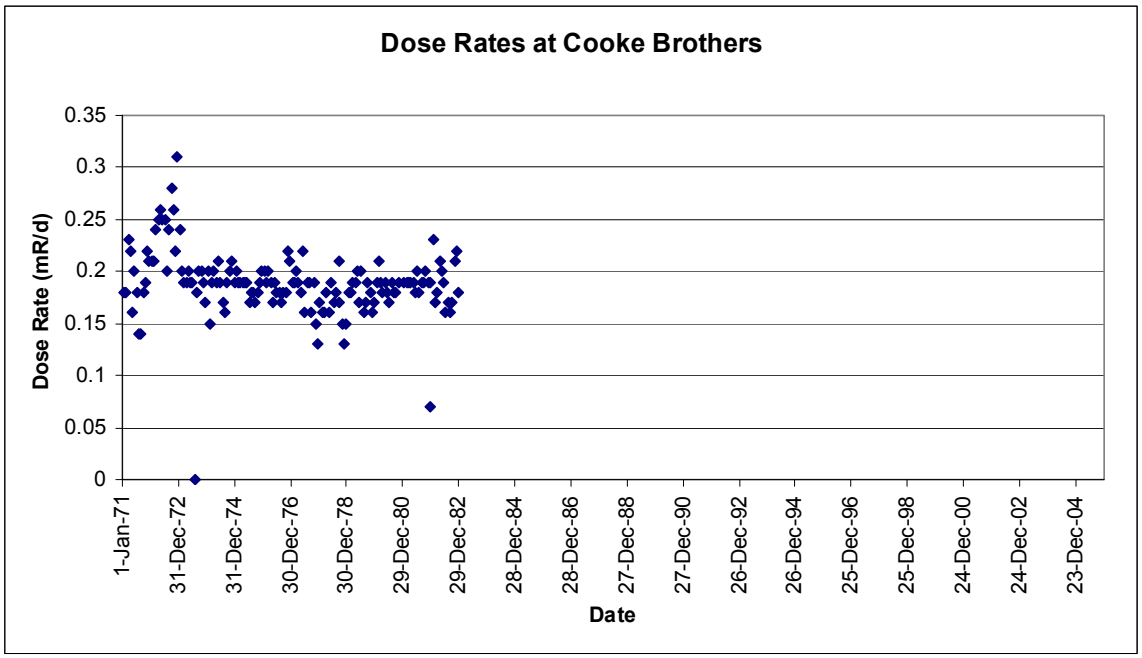


Figure A.90. Dose Rates Were Measured at Cooke Brothers from January 1971 Through December 1982. The dosimeter was located approximately 0.7 mile east of the intersection of Glade North Road and Juniper Road on the Cooke Brothers Farm.

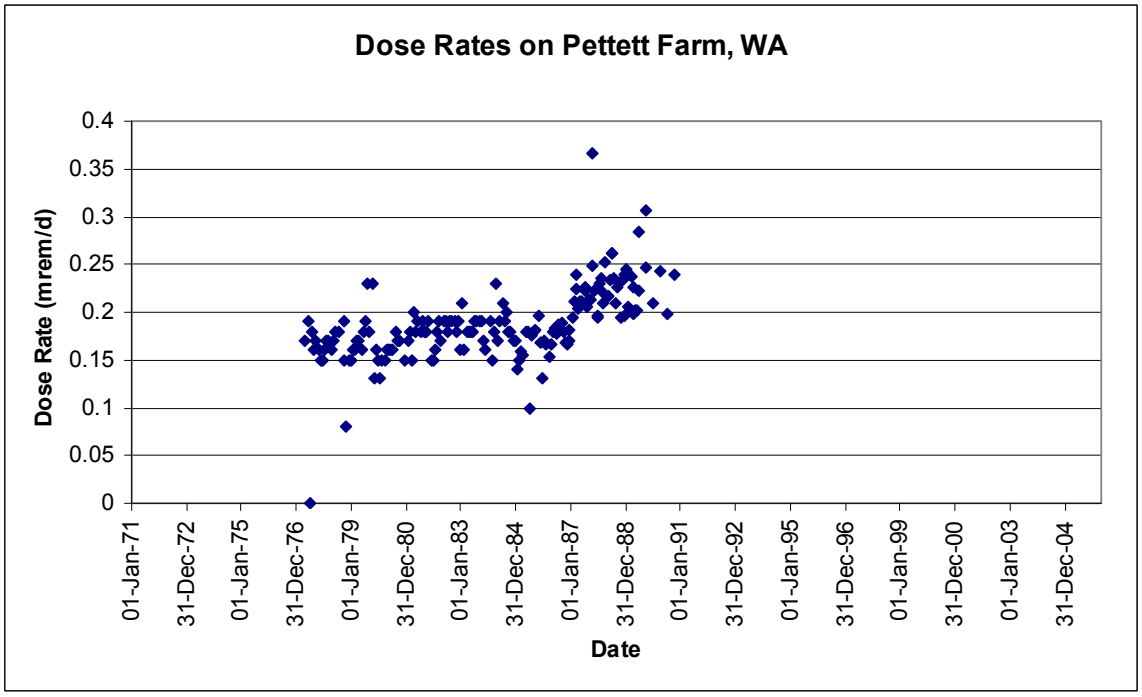


Figure A.91. Dose Rates Were Measured at Pettett Farm from May 1977 Through December 1990. The dosimeter was located on the Pettett Farm on Cottonwood Road approximately 1.8 miles from the intersection with Sagemoor Road.

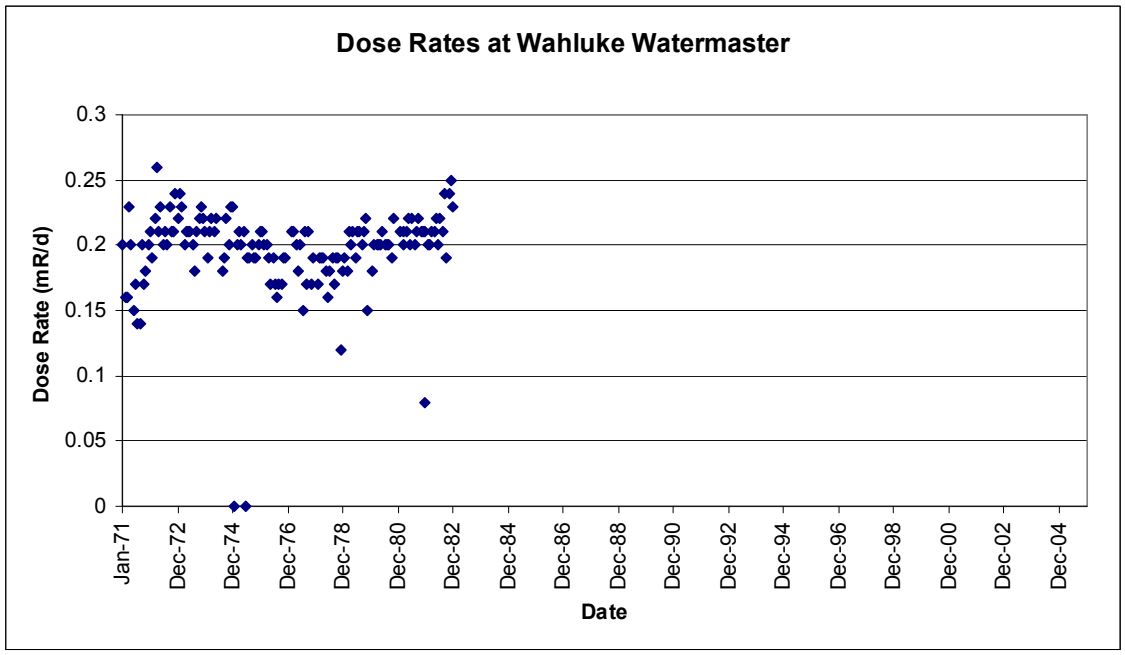


Figure A.92. Dose Rates Were Measured at Wahluke Watermaster from January 1971 Through December 1982. The dosimeter was located near the intersection of Sage Hill Road and Hendricks Road at the Wahluke Watermaster Headquarters.

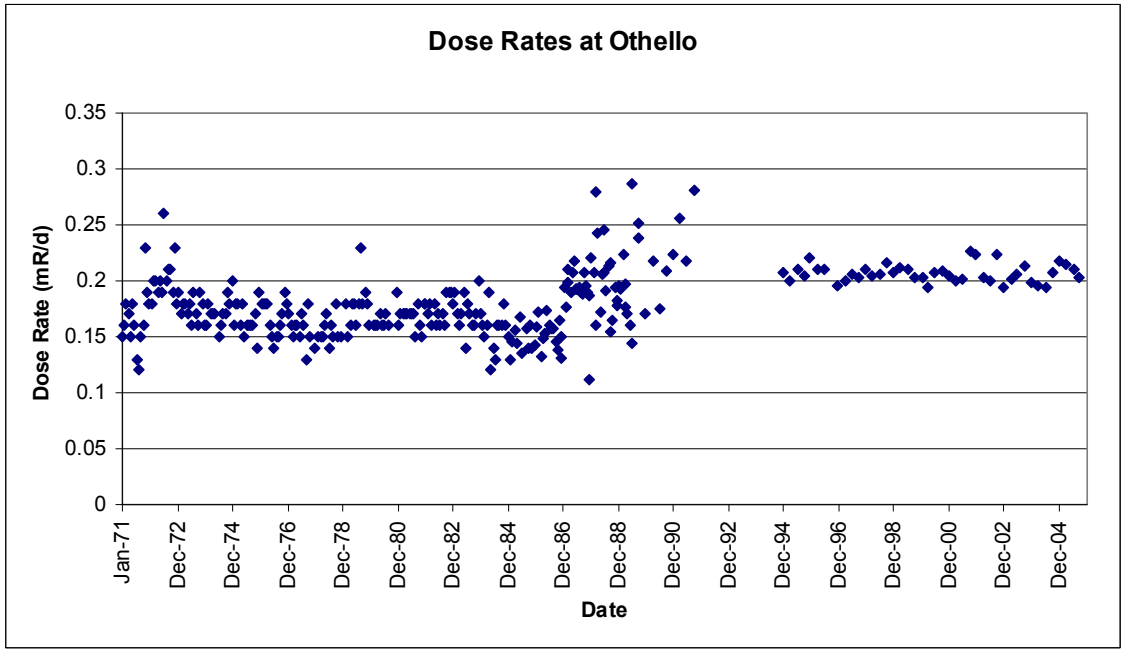


Figure A.93. Dose Rates Were Measured at Othello from January 1971 Through December 1991, Then Resumed in the First Quarter of 1995 and Continued Through December 2005. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973). In the 1970s, Othello was considered to be part of the perimeter network.

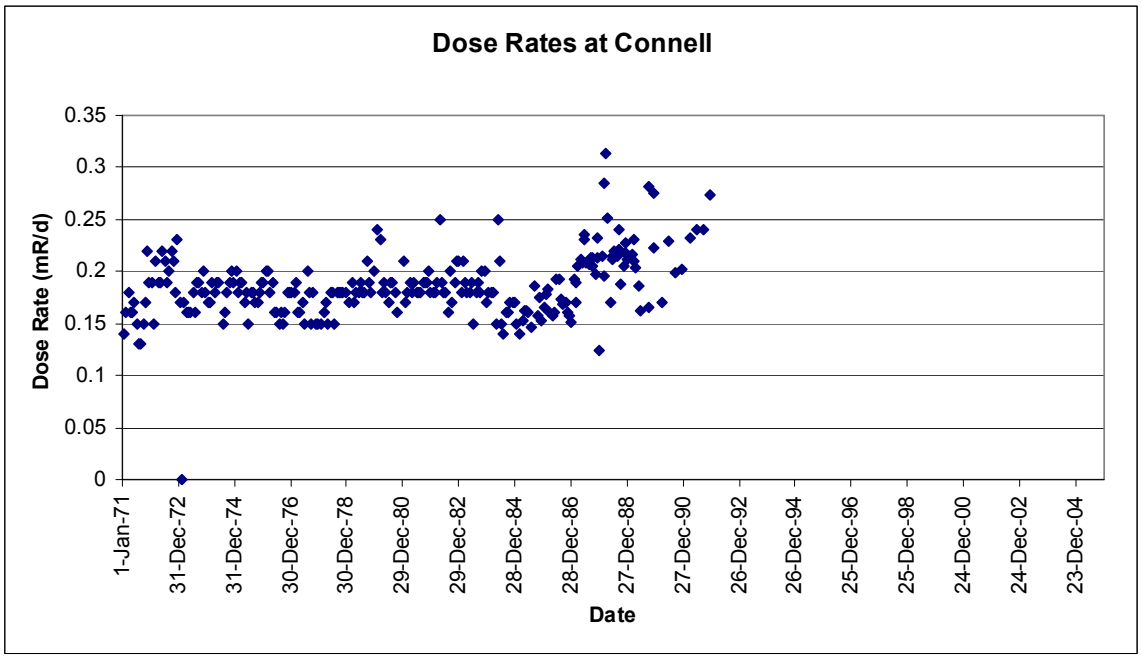


Figure A.94. Dose Rates Were Measured at Connell from January 1971 Through December 1991. The dosimeter was located within the fenced compound of the Franklin County Public Utility District on Clark Street in Connell. In the 1970s, Connell was considered to be part of the perimeter network.

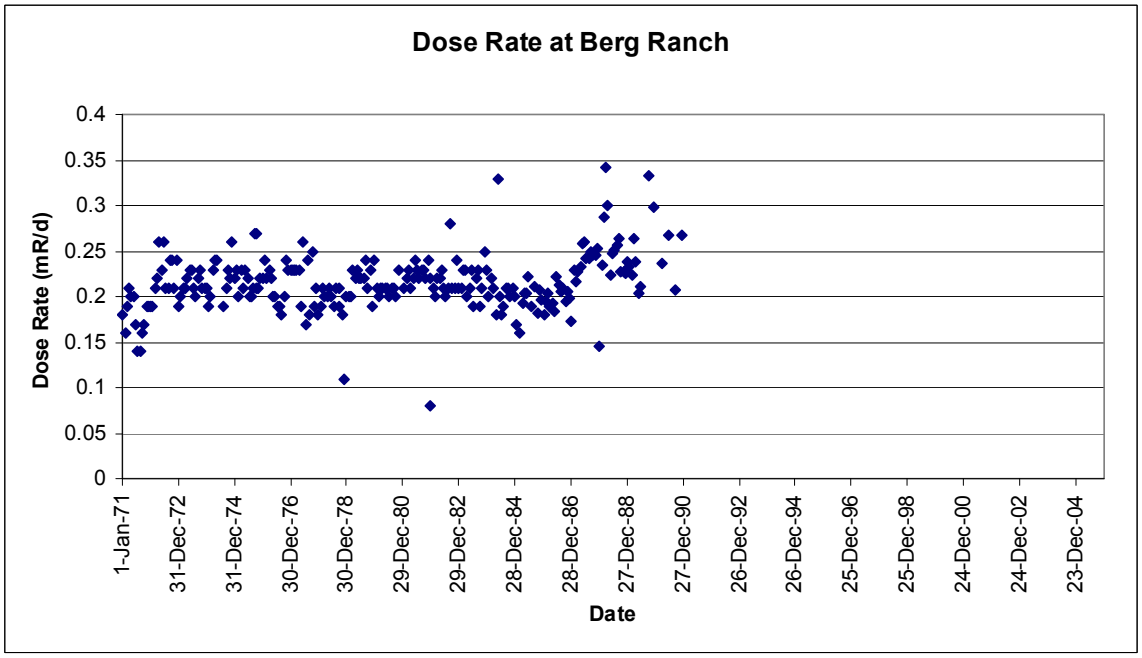


Figure A.95. Dose Rates Were Measured at Berg Ranch from January 1971 Through December 1990. No comments were found in the 1988 Hanford Site Environmental Report (Jaquish and Bryce 1989) that discussed the maximum dose rate measured in March of that year. This dosimeter was located 13 miles east of the intersection of Highway 24 and Road 24 SW, near where power lines cross Highway 24.

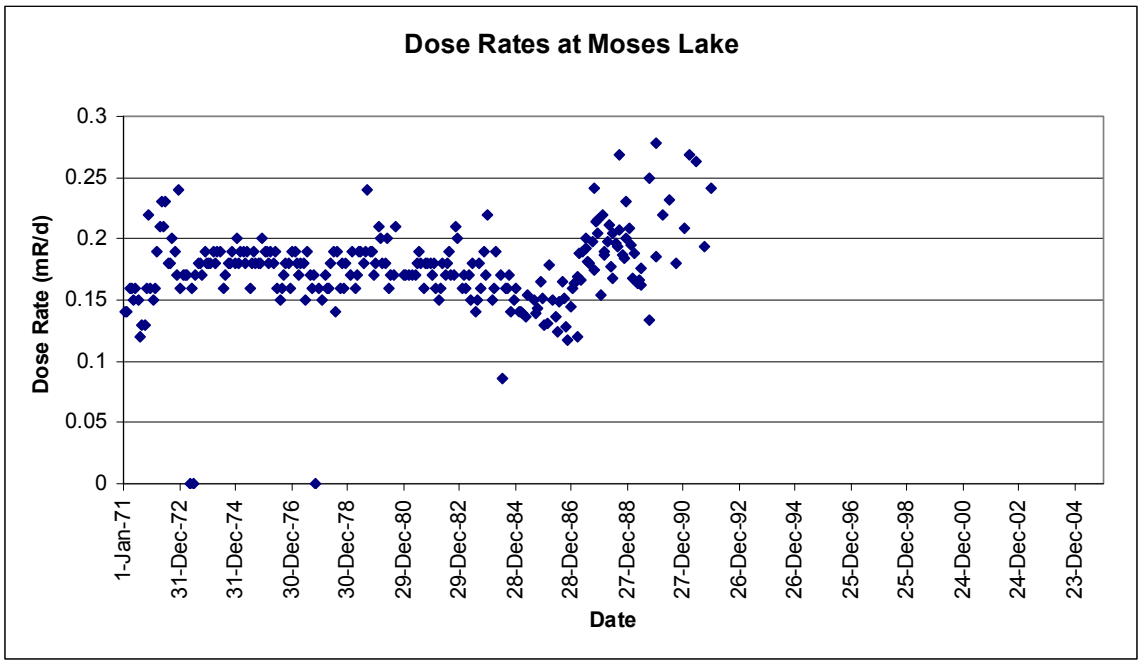


Figure A.96. Dose Rates Were Measured at Moses Lake from January 1971 Through December 1991. The dosimeter was located within the Watermaster Headquarters compound on Wheeler Road. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

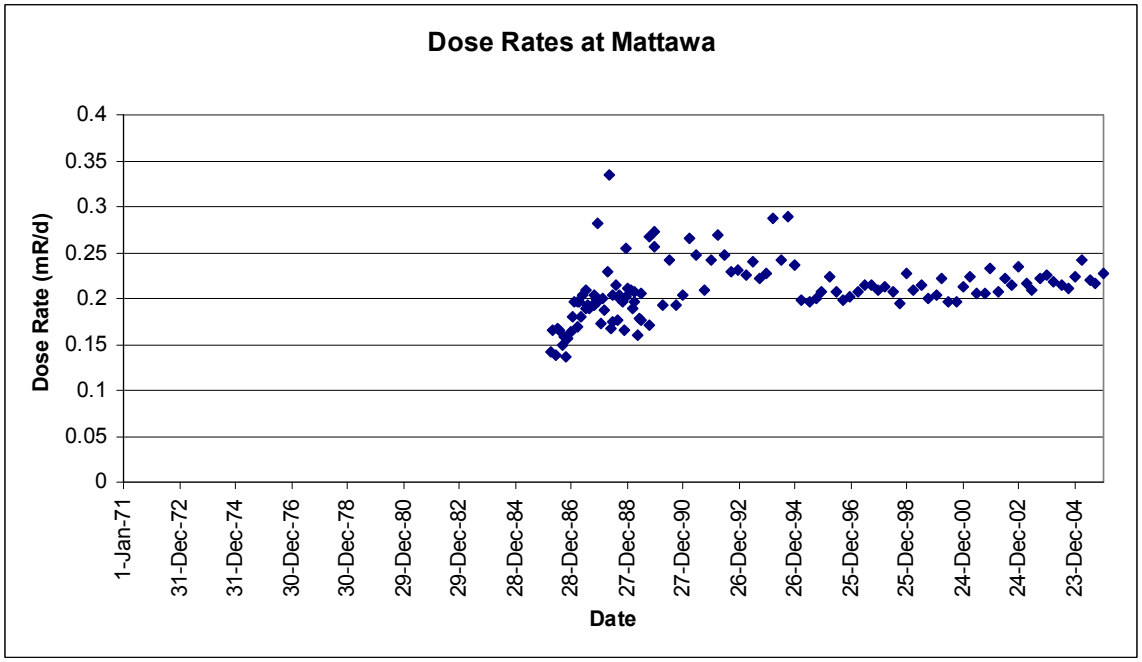


Figure A.97. Dose Rates Were Measured at Mattawa from January 1986 Through December 2005. The dosimeter was located within the fence surrounding the water tower in Mattawa.

A.3.3 Distant Communities

This section contains plots of TLD data for upland TLD sampling locations designated as Distant Communities (Figures A.98 through A.105).

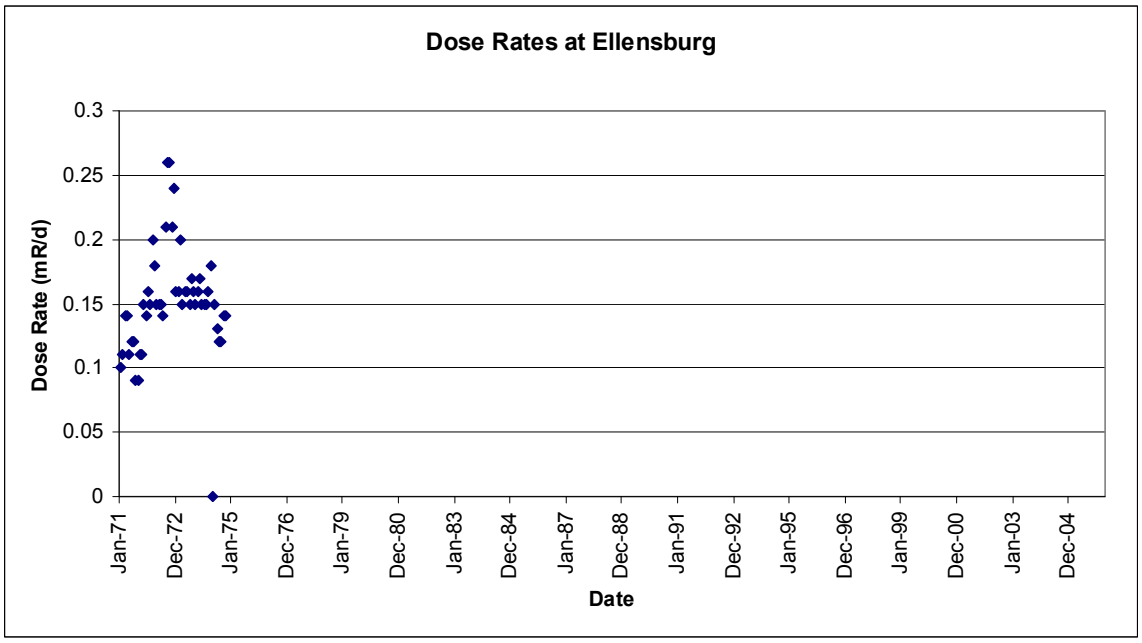


Figure A.98. Dose Rates Were Measured in Ellensburg from January 1971 Through October 1974. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

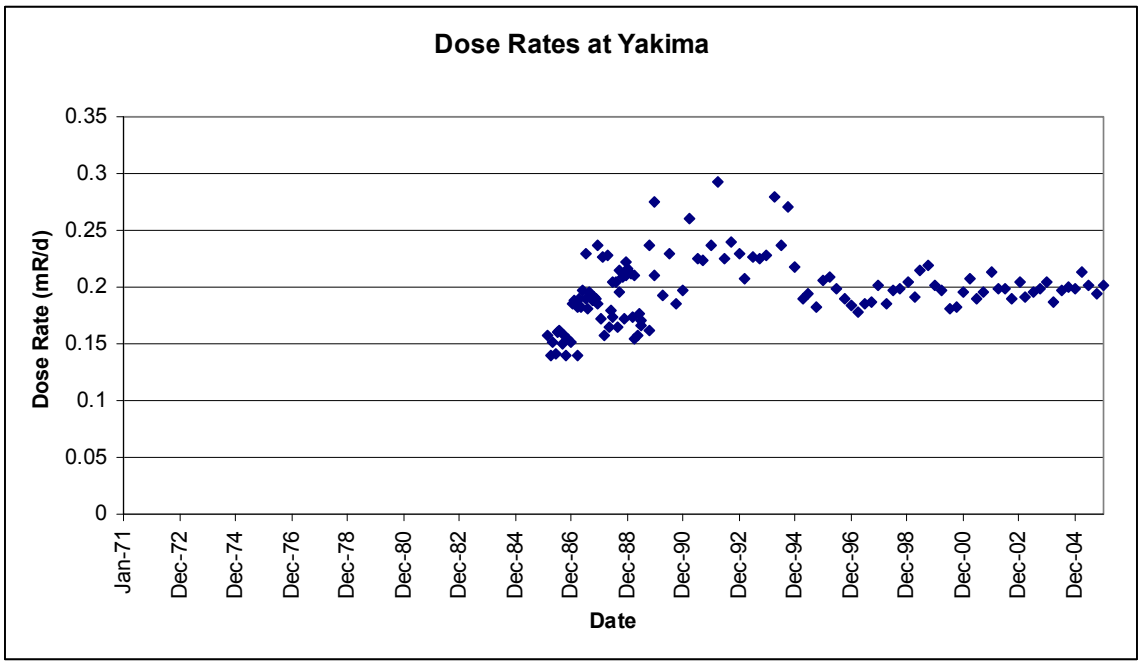


Figure A.99. Dose Rates Were Measured in Yakima from January 1986 Through December 2005. The dosimeter was located at the Yakima Airport.

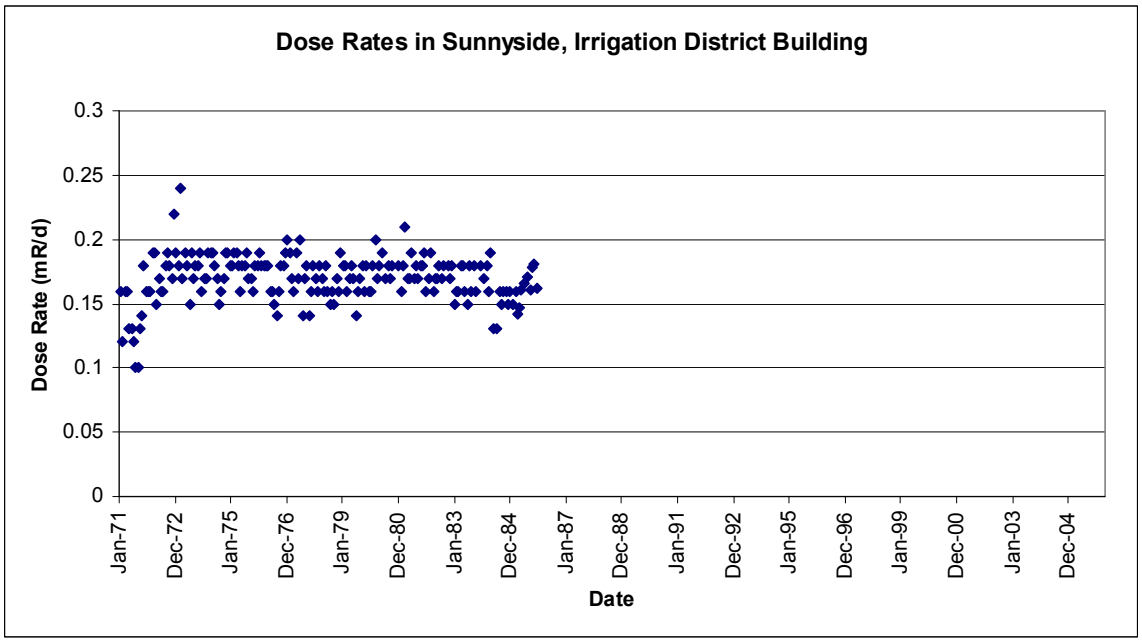


Figure A.100. Dose Rates Were Measured at Sunnyside from January 1971 Through December 1984. The dosimeter was located at the Rosa Irrigation District Compound in Sunnyside, off of 13th Street. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

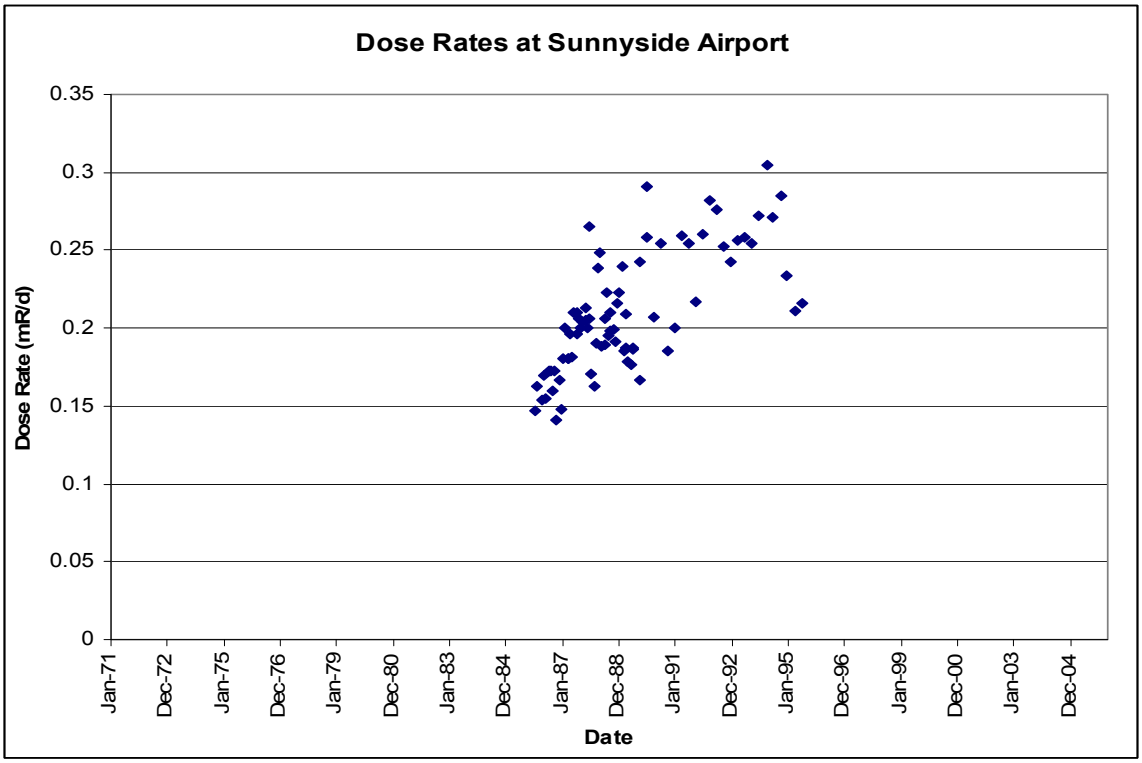


Figure A.101. Dose Rates Were Measured at the Sunnyside Airport from January 1985 Until the Location was Terminated in June 1995

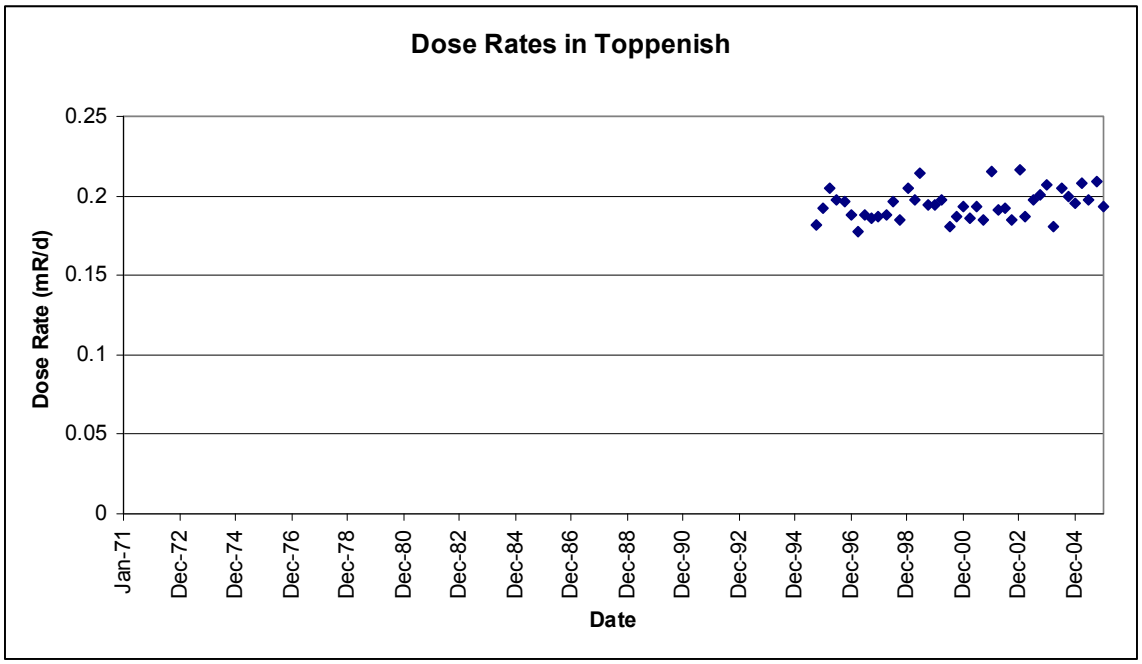


Figure A.102. Dose Rates Were Measured at Toppenish from June 1995 Through December 2005. The dosimeter was located on the fence around the community monitoring station at Heritage College in Toppenish.

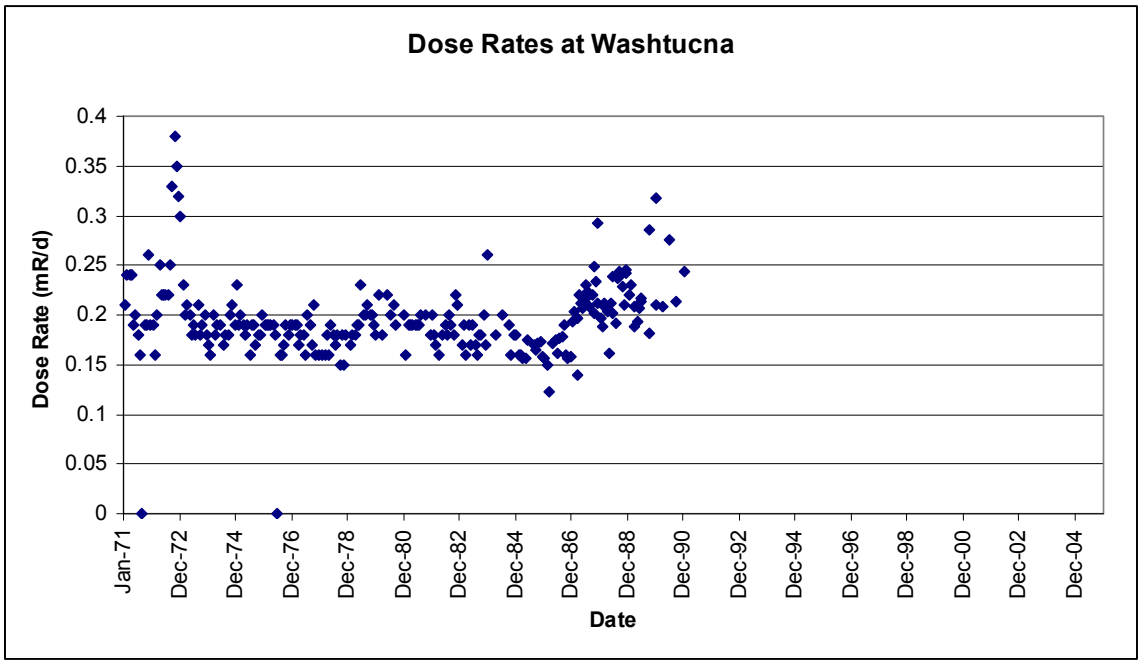


Figure A.103. Dose Rates Were Measured in Washtucna from January 1971 Through December 1990. The dosimeter was located just off the main street in Washtucna, behind the Sitka Garage. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

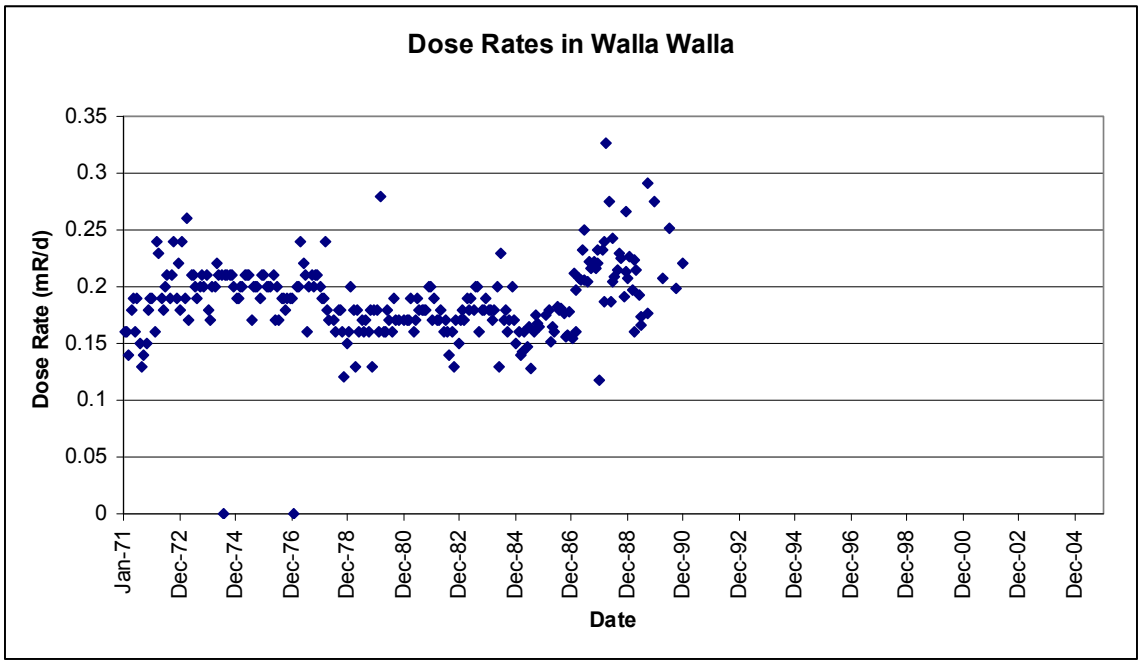


Figure A.104. Dose Rates Were Measured in Walla Walla from January 1971 Through December 1990. The dosimeter was located at the Walla Walla Airport, just past the terminal parking lot on 3rd Street. Fallout from foreign nuclear weapons tests in October 1971 and March 1972 resulted in an abrupt increase in measured exposure rates in early 1972 (Bramson and Corley 1973).

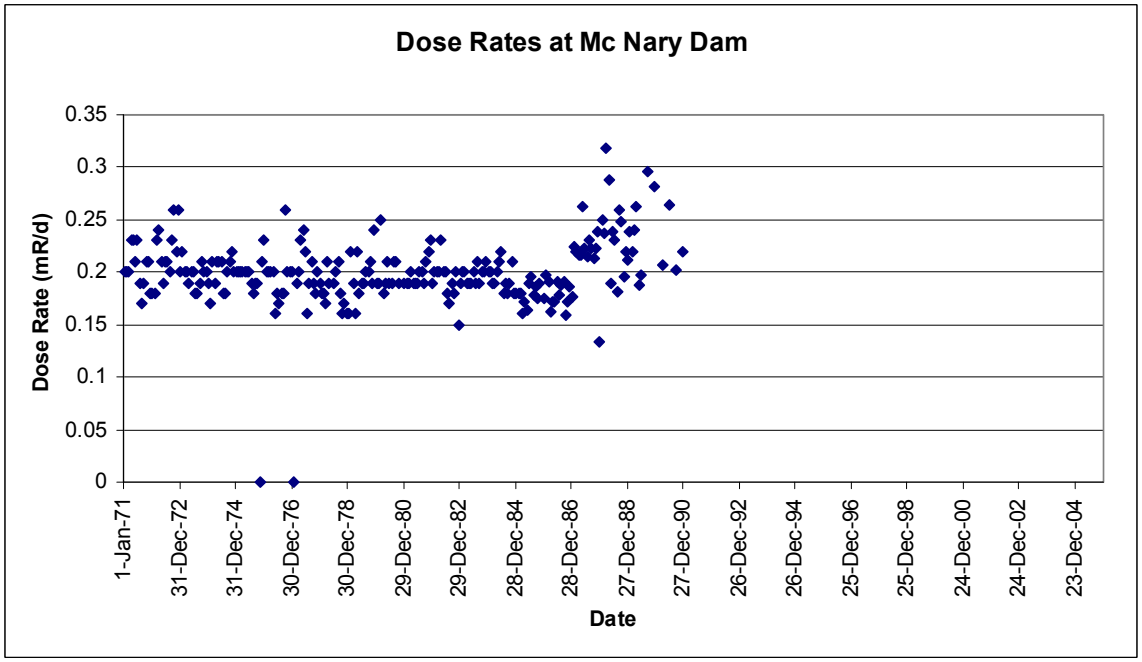


Figure A.105. Dose Rates Were Measured at McNary Dam from January 1971 Through December 1990. The dosimeter was located on the fence around the power substation on McNary Dam Road.

A.4 References

40 CFR 61. 2008. "National Emission Standards for Hazardous Air Pollutants." *Code of Federal Regulations*, U.S. Environmental Protection Agency.

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Appendix B

TLD Graphical Data Summaries by Sample Location for Riparian (Columbia River Shoreline) Locations on the Hanford Site

Appendix B

TLD Graphical Data Summaries by Sample Location for Riparian (Columbia River Shoreline) Locations on the Hanford Site

This appendix contains graphs of thermoluminescent dosimeter (TLD) results as reported in the Hanford Environmental Information System (HEIS) from late 1970 through December 2005. For some locations, data from the surveillance of external radiation measurements were collected for only a few years. Some of the graphs in this appendix distinguish between TLD designs; however, none of them specify the duration of deployment (biweekly, monthly, or quarterly). At some locations, dosimeters of different designs were co-deployed to meet different objectives. In some cases, TLD surveillance of external radiation measurements was conducted for only a few years. Also, over the duration of the 35-year program, the actual location of a dosimeter may have moved slightly and different names may have been used to identify particular locations. This appendix captures and documents those changes for each location.

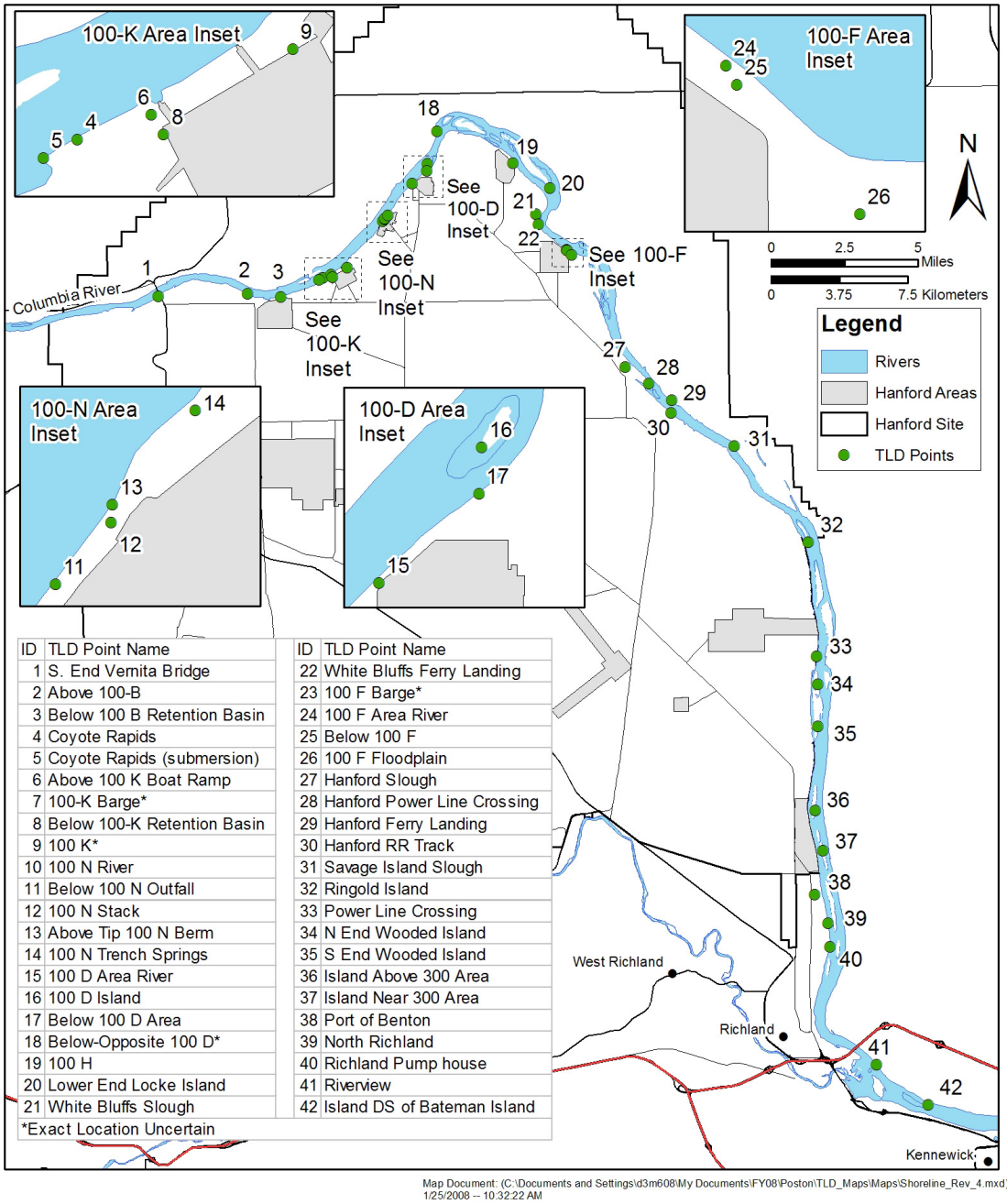
By definition, shoreline TLDs were located immediately adjacent to the shoreline. When located near facilities, the TLDs were positioned between the perimeter of the facility and the river (Figure B.1). Most were located on the Benton County side of the Columbia River, but a few were located on the opposite shoreline in Franklin County. Shoreline TLD locations did not change much over the 35-year operating history of the TLD program. Most changes occurred near the reactor areas in response to operations at those sites.

Shoreline TLD locations that were operational in the late 1990s through the time when the surveillance program was terminated in 2005 were established using global positioning system (GPS) technology and coordinates were obtained at the TLD sampling locations (Table B.1). For locations that existed prior to this time, the locations were approximated using commercial software (Google, Inc. 2009) based on maps in annual environmental reports, descriptions of locations in the locations manual,[1] historic internal versions of location manuals, and project files. For some of the older locations, where TLDs were deployed for only a short time (e.g., barges on the river), TLD coordinates could not be established. All of the GPS coordinates for these early locations are best estimates based on available information.

B.1 General Observations

The comments presented for Appendix A also apply here. TLDs deployed near the 100-N Area reflected skyshine emanating from the 100-N liquid water disposal trenches. TLD locations are shown in Figure B.1 and mapping coordinates and years of deployment are shown in Table B.1. Figure B.1 is a composite of the data contained in Figures B.3 through B.10.

[1] Pacific Northwest Laboratories (PNL). 1983. *Environmental Sampling Locations Manual*, Battelle-Pacific Northwest Laboratories, PNL-MA-514, Richland, Washington (internal manual).



ID	TLD Point Name	ID	TLD Point Name
1	S. End Vernita Bridge	22	White Bluffs Ferry Landing
2	Above 100-B	23	100 F Barge*
3	Below 100 B Retention Basin	24	100 F Area River
4	Coyote Rapids	25	Below 100 F
5	Coyote Rapids (submersion)	26	100 F Floodplain
6	Above 100 K Boat Ramp	27	Hanford Slough
7	100-K Barge*	28	Hanford Power Line Crossing
8	Below 100-K Retention Basin	29	Hanford Ferry Landing
9	100 K*	30	Hanford RR Track
10	100 N River	31	Savage Island Slough
11	Below 100 N Outfall	32	Ringold Island
12	100 N Stack	33	Power Line Crossing
13	Above Tip 100 N Berm	34	N End Wooded Island
14	100 N Trench Springs	35	S End Wooded Island
15	100 D Area River	36	Island Above 300 Area
16	100 D Island	37	Island Near 300 Area
17	Below 100 D Area	38	Port of Benton
18	Below-Opposite 100 D*	39	North Richland
19	100 H	40	Richland Pump house
20	Lower End Locke Island	41	Riverview
21	White Bluffs Slough	42	Island DS of Bateman Island
*Exact Location Uncertain			

Figure B.1. Shoreline TLD Sampling Locations on the Columbia River

Table B.1. GPS Coordinates and Years of Operations for TLD Locations Along the Columbia River Shoreline

Location Name	Latitude	Longitude	Years of Operation	Page
South End Vernita Bridge[(a)]	46.639731	-119.73224	2000–2005	B.5
Above 100-B	46.640275	-119.66859	1980–2005	B.6
Below 100 B Retention Basin	46.638786	-119.6447	1980–2005	B.6
Coyote Rapids	46.6479	-119.61466	2004–2005	B.7
Coyote Rapids (submersion)	46.646921	-119.61743	1973–1992	B.7
Above 100-K Boat Ramp	46.649262	-119.60866	1975–2005	B.8
100-K Barge	NA	NA	1970–1972	B.8
Below 100-K Retention Basin	46.64813	-119.6077	1980–1982	B.9
100–K Area	46.65282	-119.5972	NA	
100-N River	NA	NA	1972–1977	B.10
Below 100-N Outfall	46.675371	-119.57121	1981–2005	B.10
100-N Stack	46.67643	-119.5698	1981–1997	B.11
Above Tip 100-N Berm	46.676736	-119.56976	1981–2005	B.11
100-N Trench Springs	46.678338	-119.56766	1977–2005	B.12
100-D Area River	46.693794	-119.54968	1972–1974	B.13
100-D Island	46.703472	-119.53883	1971–1974; 1992–2005	B.13
Below 100-D Area	46.700119	-119.53918	1980–2005	B.14
Below-Opposite 100-D Area	46.71951	-119.5315	1975–1997	B.14
100-H Area	46.703168	-119.4777	1972; 2000–2005	B.15
Lower End Locke Island	46.690773	-119.45117	1975–2005	B.16
White Bluffs Ferry Landing	46.672892	-119.45968	1975–2005	B.16
White Bluffs Slough	46.678119	-119.4616	1980–2005	B.17
100-F Barge	NA	NA	1971	B.17
100-F Area River	46.6603	-119.4398	1972–1974	B.18
Below 100-F	46.65995	-119.43953	1975–2005	B.18
100-F Floodplain	46.657599	-119.43636	1980–2005	B.19
Hanford Slough	46.601879	-119.39936	1980–2005	B.20
Hanford Power Line Crossing	46.593725	-119.3824	1972–2005	B.20
Hanford Ferry Landing	46.58535	-119.3663	1975–1997	B.21
Hanford RR Track	46.579167	-119.36686	1972–2005	B.21
Savage Island Slough	46.562143	-119.32226	1980–2005	B.22
Ringold Island	46.51433	-119.27016	1975–2005	B.23
Power Line Crossing	46.457849	-119.26585	1975–2005	B.23
North End Wooded Island	46.44426	-119.2651	1980–1997	B.24
South End Wooded Island	46.423391	-119.26541	1971–2005	B.24
Island Above 300 Area	46.381927	-119.26859	1991–2005	B.25
Island Near 300 Area	46.362253	-119.26318	1980–2005	B.26
Port of Benton	46.340692	-119.26969	1992–2005	B.26
North Richland	46.326386	-119.26057	2002–2005	B.27
Richland Pump house	46.314714	-119.25963	1971–1992	B.28
Riverview	46.25615	-119.22756	2005	B.28
Island Downstream (DS) of Bateman Island	46.23599	-119.19143	1980–2005	B.29

(a) Prior to 2000, this was classified as a perimeter location.
NA = Data were not available.

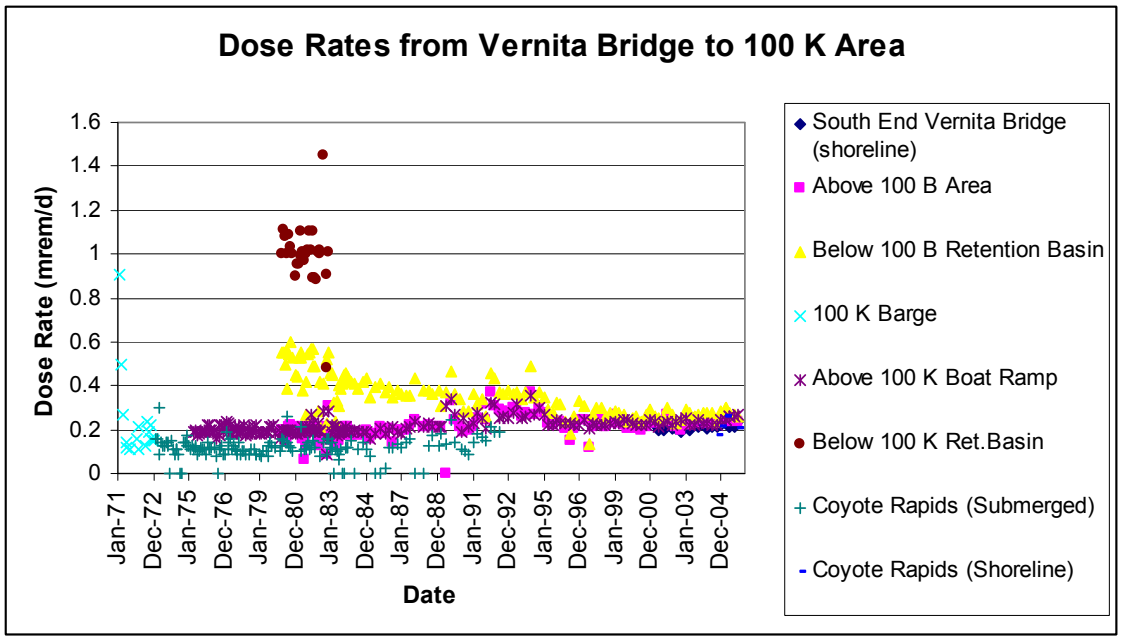


Figure B.2. Results from Dosimeters Located Along the Shoreline from the Vernita Bridge to the 100-K Area. This is a composite of the data contained in Figures B.3 through B.10. The high value of 9.57 mrem/d (100-K Barge dated January 1971) has been omitted from this graph to show detail at other locations.

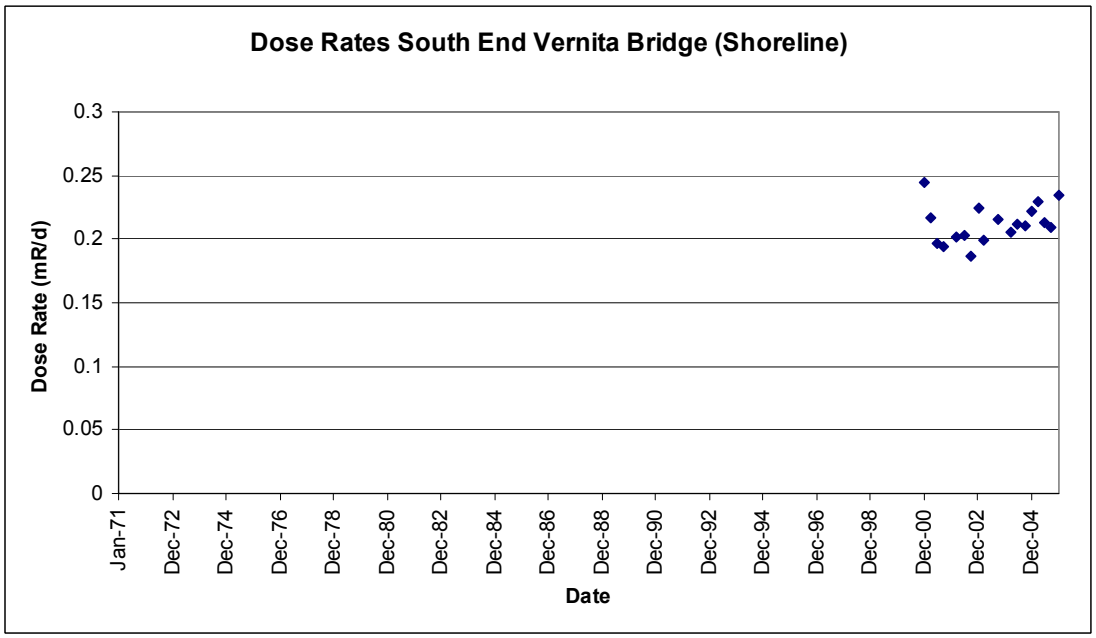


Figure B.3. Dose Rates Were Measured at the South End of Vernita Bridge as a Shoreline Location Beginning in the Fall of 2000 and Continued Through December 2005. The dosimeter was located at the south end of Vernita Bridge among some trees on the upstream side of the bridge near the rest area at Vernita Bridge. It then was moved to downstream side of the bridge due to vandalism. This location was considered a background location for shoreline dose rates.

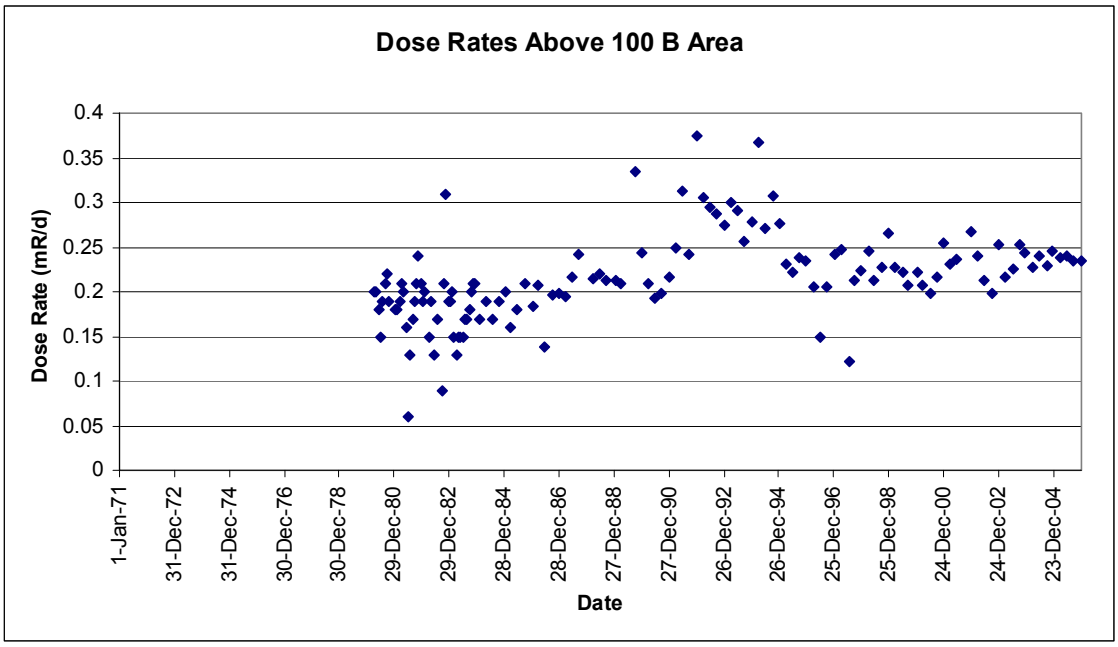


Figure B.4. Dose Rates Were Measured Above the 100-B Area from April 1980 Through December 2005. The dosimeter was located about 3 miles downstream of the Vernita Bridge, on the Benton County side of the river. This location was considered a background location for shoreline dose rates.

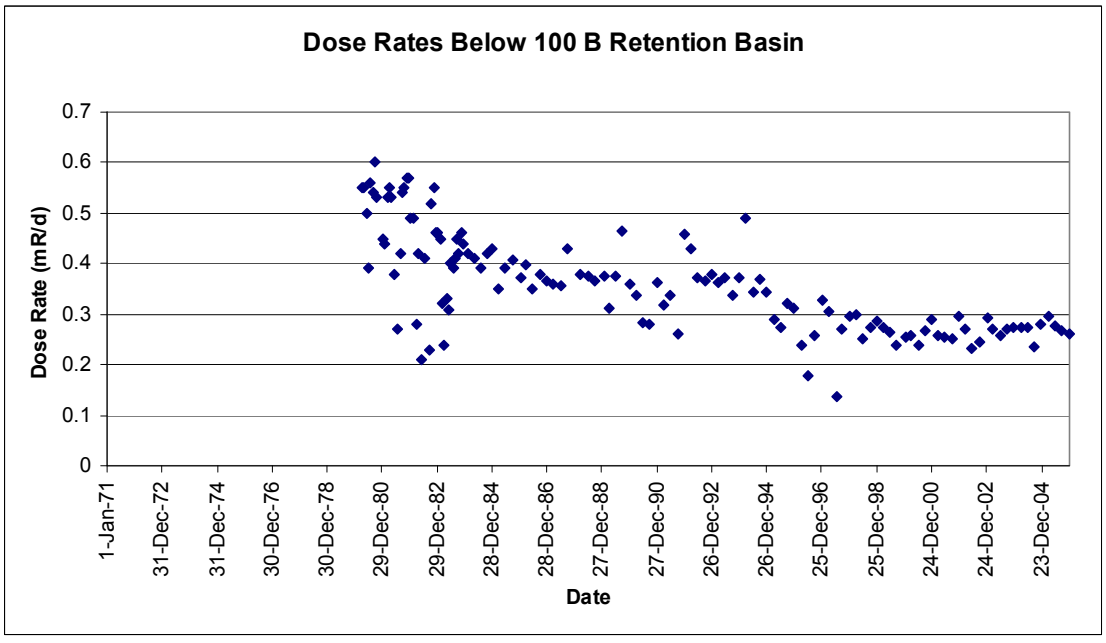


Figure B.5. Dose Rates Were Measured Below the 100-B Retention Basin from April 1980 Through December 2005. The dosimeter was located in the boulder-filled ravine of the outfall coming from the 100-B Retention Basin.

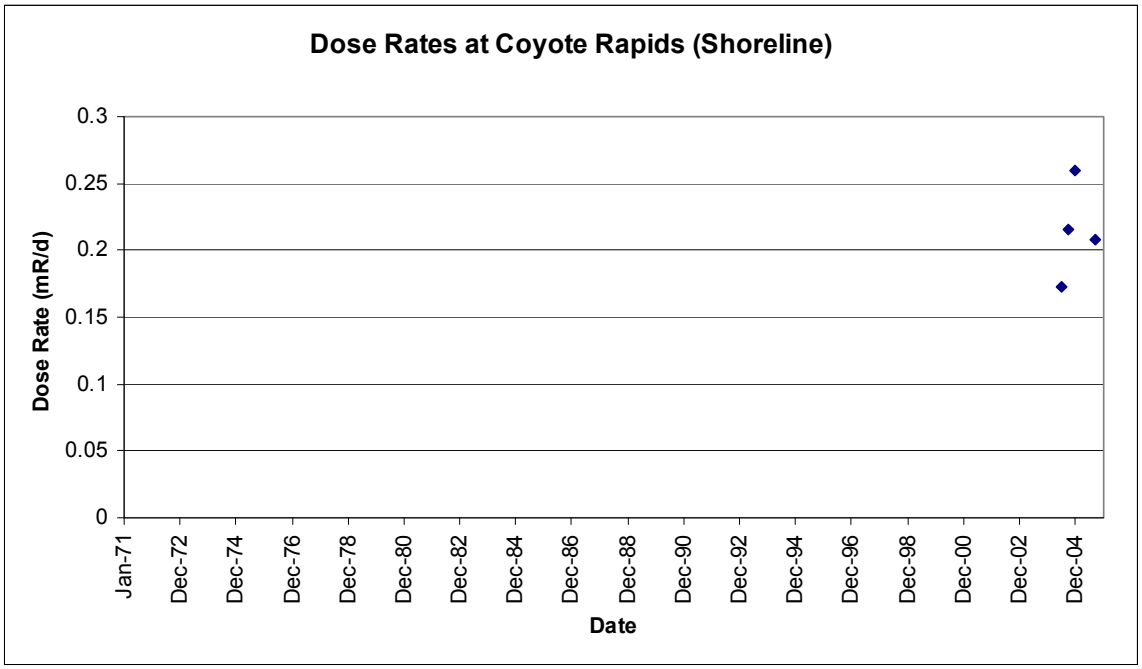


Figure B.6. Dose Rates Were Measured at the Coyote Rapids Shoreline Beginning in June 2004 and Continued Through December 2005. This location was in a slight depression in the peninsula at Coyote Rapids and was established after a shoreline survey reported elevated dose rates on the peninsula.

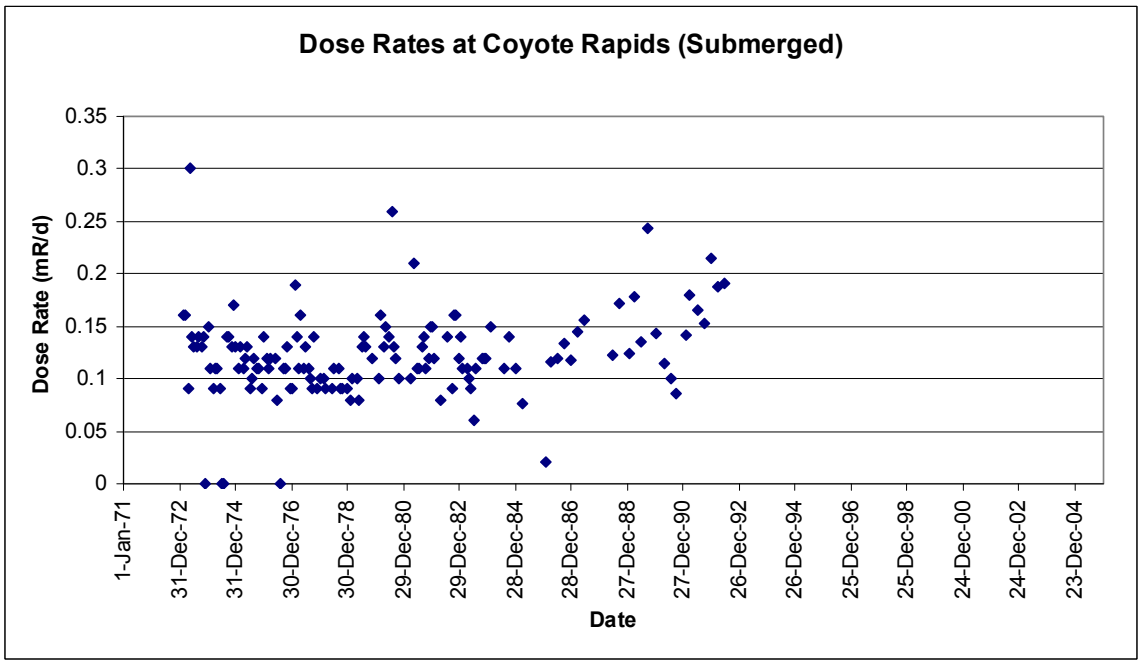


Figure B.7. Submersion Dose Rates Were Measured in Coyote Rapids from January 1973 Through June 1992. The dosimeter was located in the pool created behind Coyote Rapids. This dosimeter was established to provide an estimate of penetrating radiation dose that could be received by a person immersed in the water.

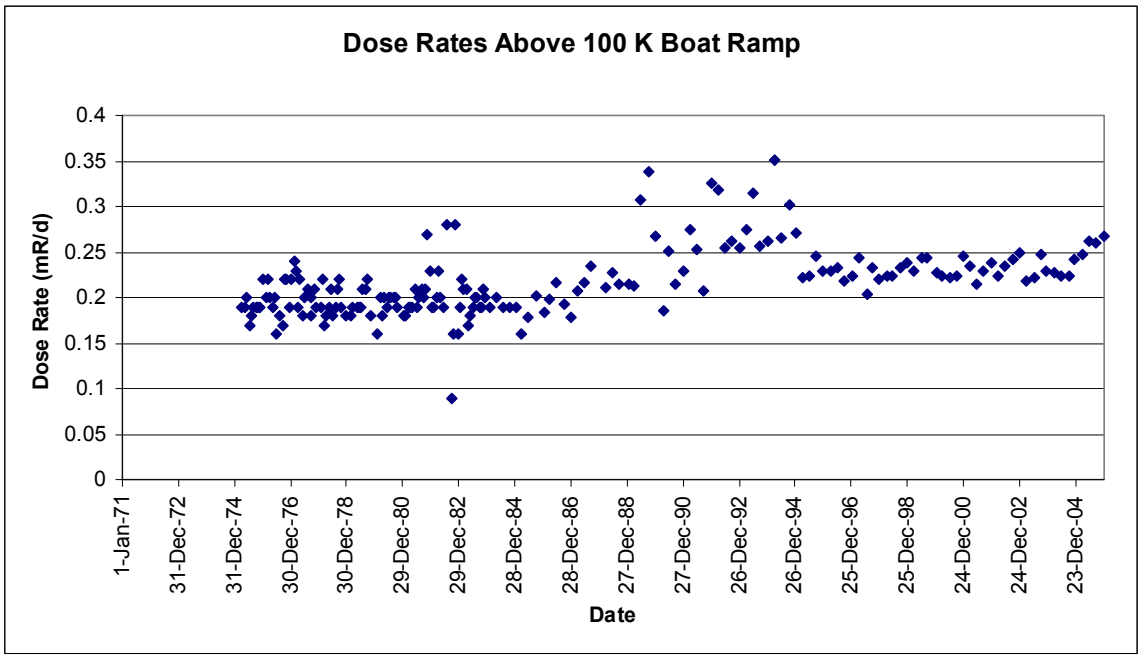


Figure B.8. Dose Rates Were Measured at the 100-K Boat Ramp from March 1975 Through December 2005. The dosimeter was located west of the 100-K West Area perimeter fence on the river bank near a clump of trees.

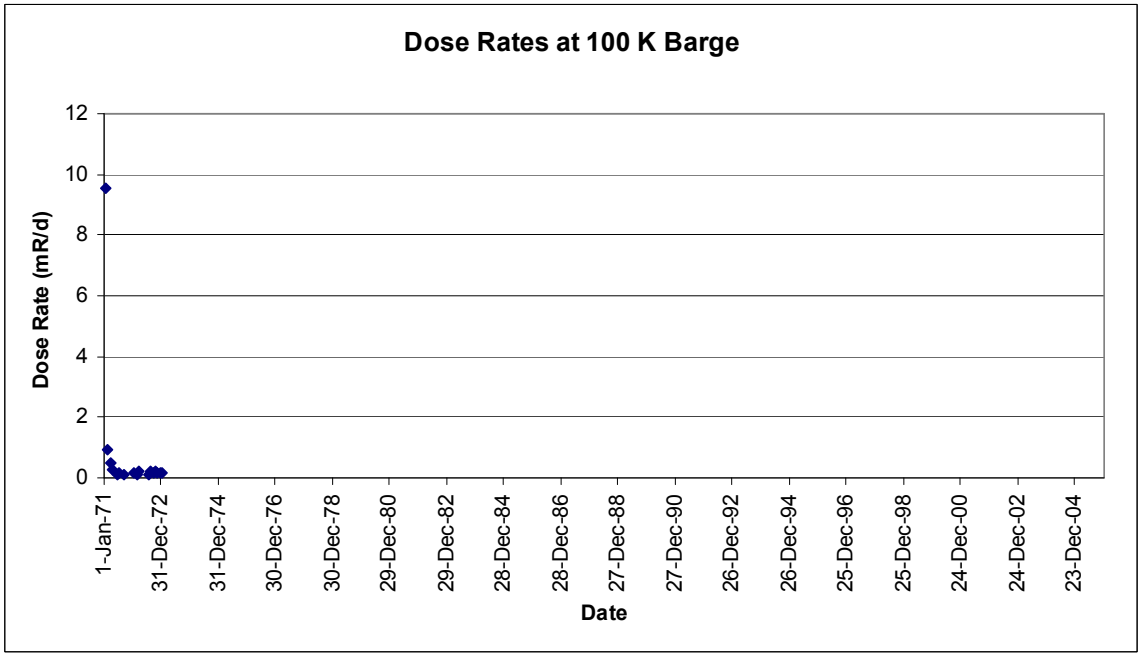


Figure B.9. Dose Rates Were Measured at 100-K Barge from December 1970 Through December 1972. The barge was positioned over the water outfall pipe. The dosimeter was located below the surface of the Columbia River and in 1971, the dose rates were averaged over two 6-month periods and reported in Bramson and Corley (1972b).

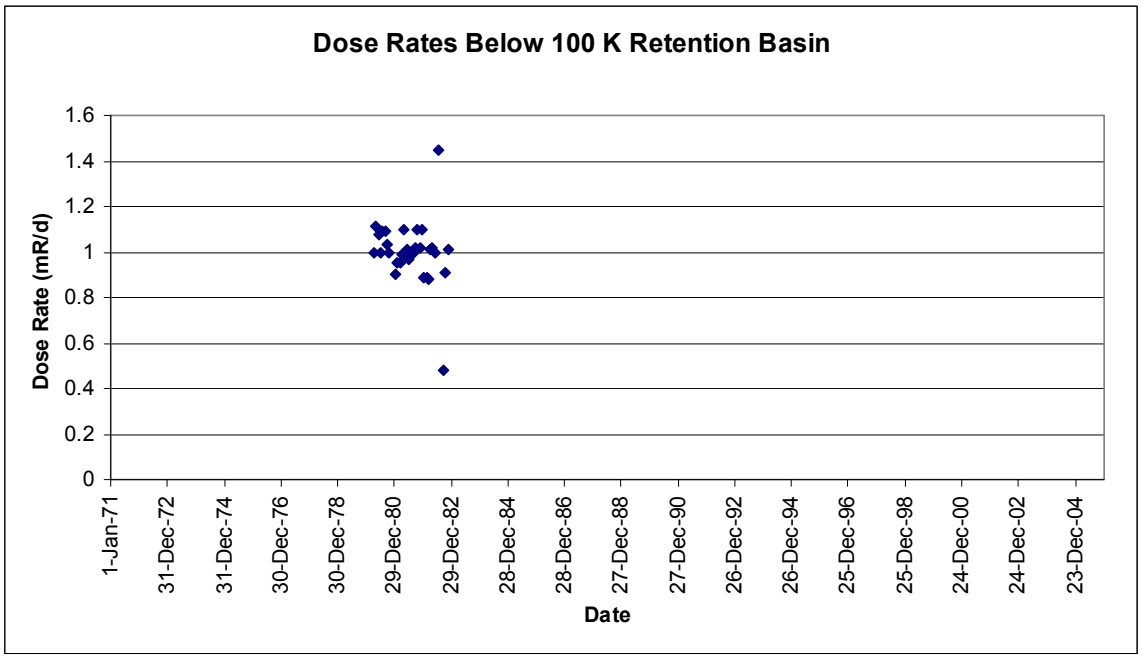


Figure B.10. Dose Rates Were Measured Below the 100-K Retention Basin from April 1980 Through November 1982. The dosimeter was located between the 100-B/C and 100-K Areas and had the highest dose rate measured at onsite locations in 1982 (Sula et al. 1983).

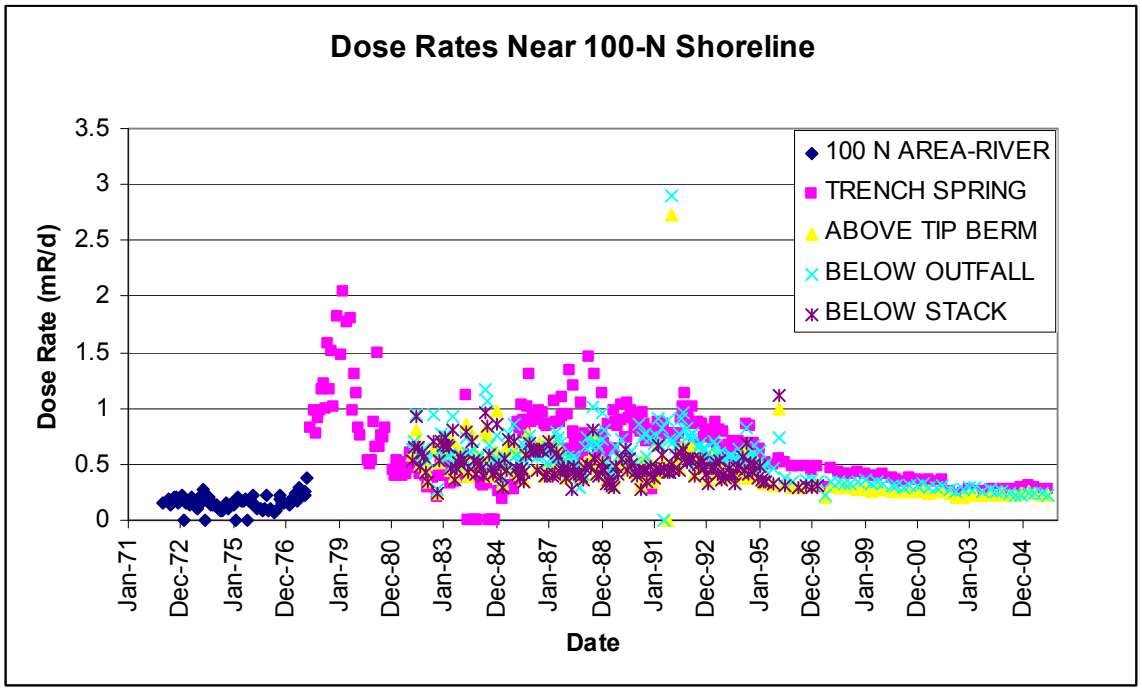


Figure B.11. Composite Results from Dosimeters Located Along the Shoreline Around 100-N Reactor (Figures B.12 through B.16). N Reactor operated from December 1963 through January 1987.

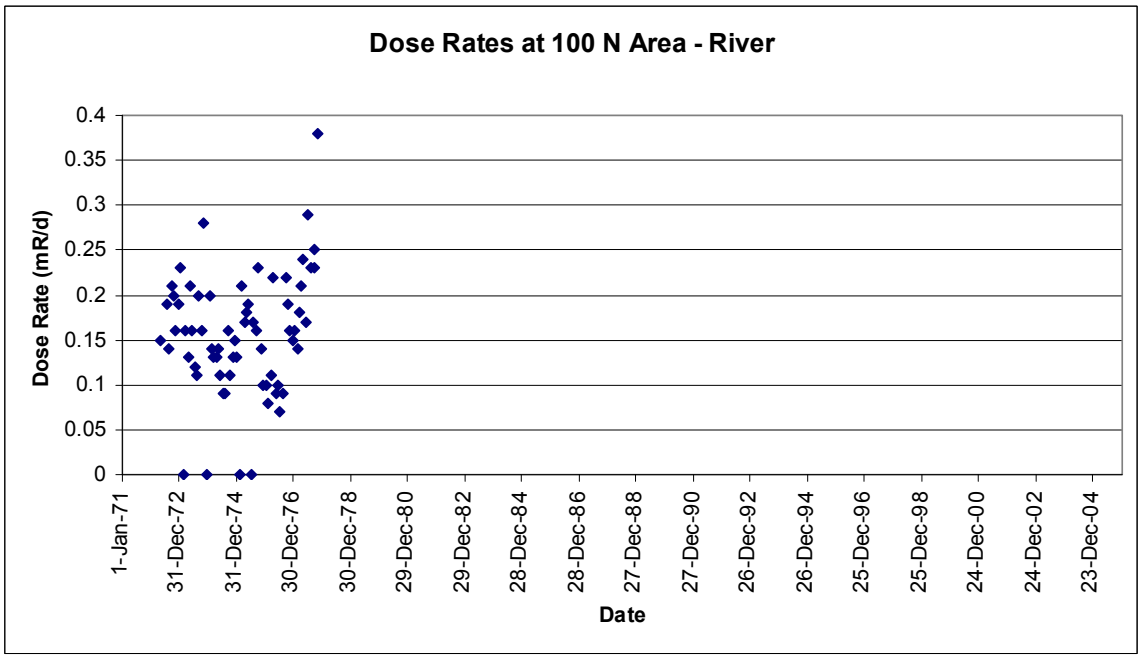


Figure B.12. Dose Rates Were Measured at 100-N Area River from March 1972 Through October 1977. No specific location was found.

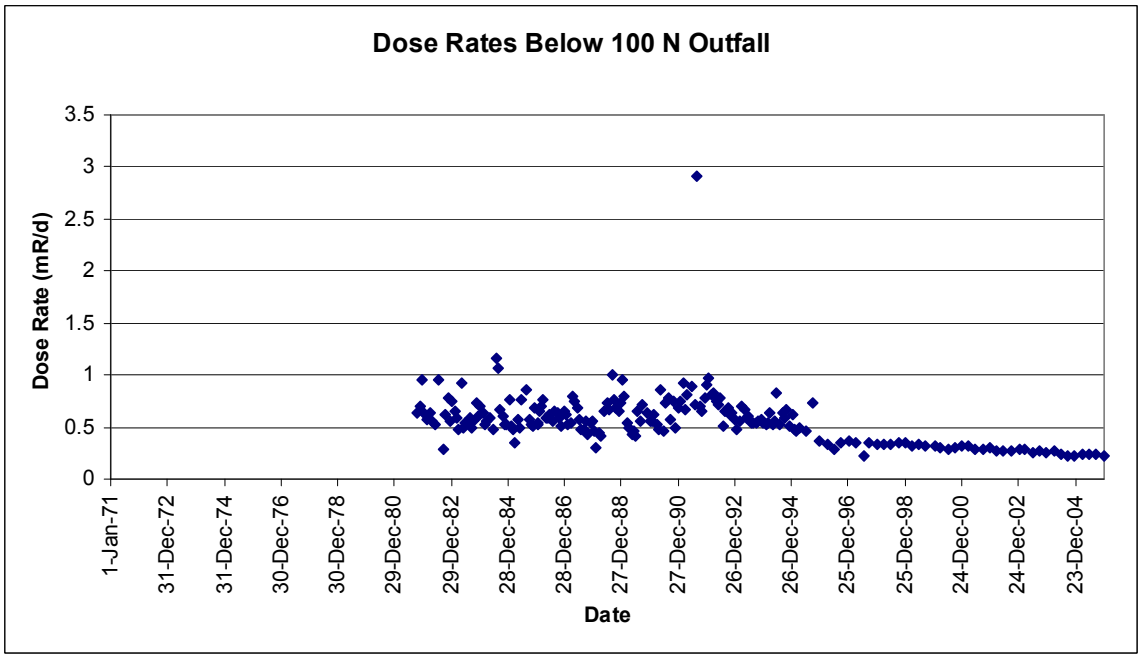


Figure B.13. Dose Rates Were Measured Below the 100-N Outfall from October 1981 Through December 2005. The dosimeter was located along the 100-N shoreline, downstream of the 100-N water outfall, near the high-water mark. The highest dose rate was measured in August 1991 and was attributed to waste management practices within the 100-N Area (Woodruff et al. 1992).

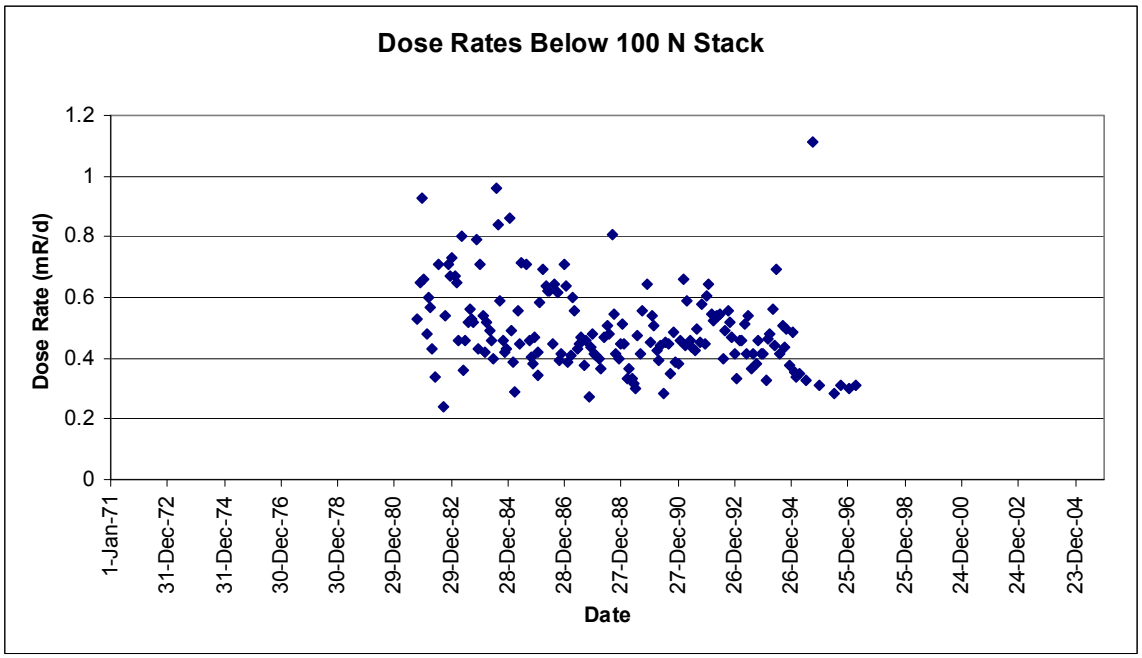


Figure B.14. Dose Rates Were Measured Below the 100-N Stack from October 1981 Through March 1997. The dosimeter was located along the 100-N shoreline, directly below the 100-N stack, near the high-water mark. The highest dose rate, measured in August 1995, was attributed to moving reactor fuel core spacers from a storage vault, transferring them to rail cars, and moving them to a new location (Dirkes and Hanf 1996).

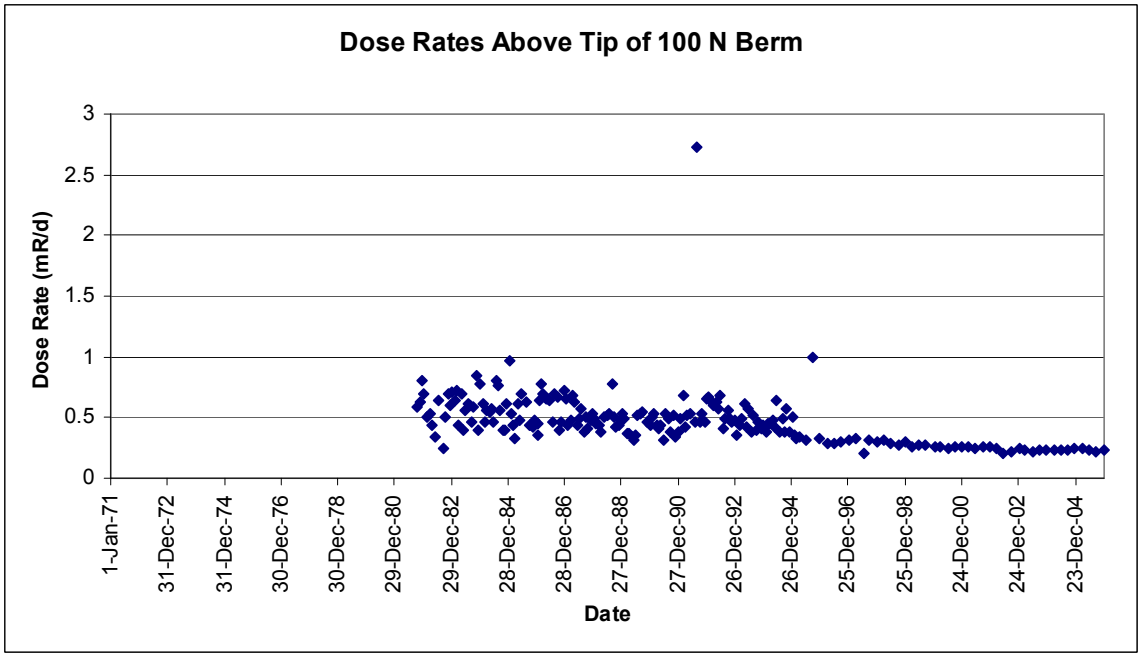


Figure B.15. Dose Rates Were Measured Above the Tip of the 100-N Berm from October 1981 Through December 2005. The dosimeter was located along the 100-N shoreline, upstream of a berm, near the high-water mark. The highest dose rate, measured in August 1991, was attributed to waste management practices within the 100-N Area (Woodruff et al. 1992).

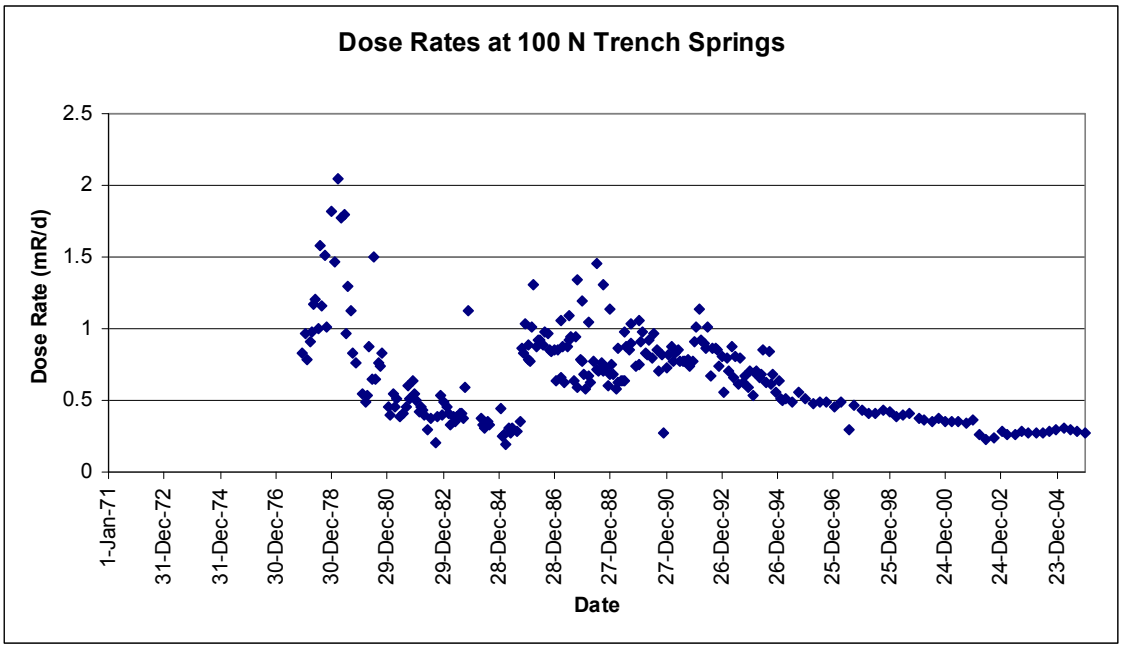


Figure B.16. Dose Rates Were Measured at the 100-N Trench Springs from October 1977 Through December 2005. The dosimeter was located near the high-water mark, downstream from the 100-N stack, near a small tan building on the shoreline. The elevated dose rates measured in the late 1970s was attributed to scattered radiation from N-Reactor operations (Huston and Blumer 1980). Data gaps in 1983 and 1984 were due to construction or excavation activities along the shoreline.

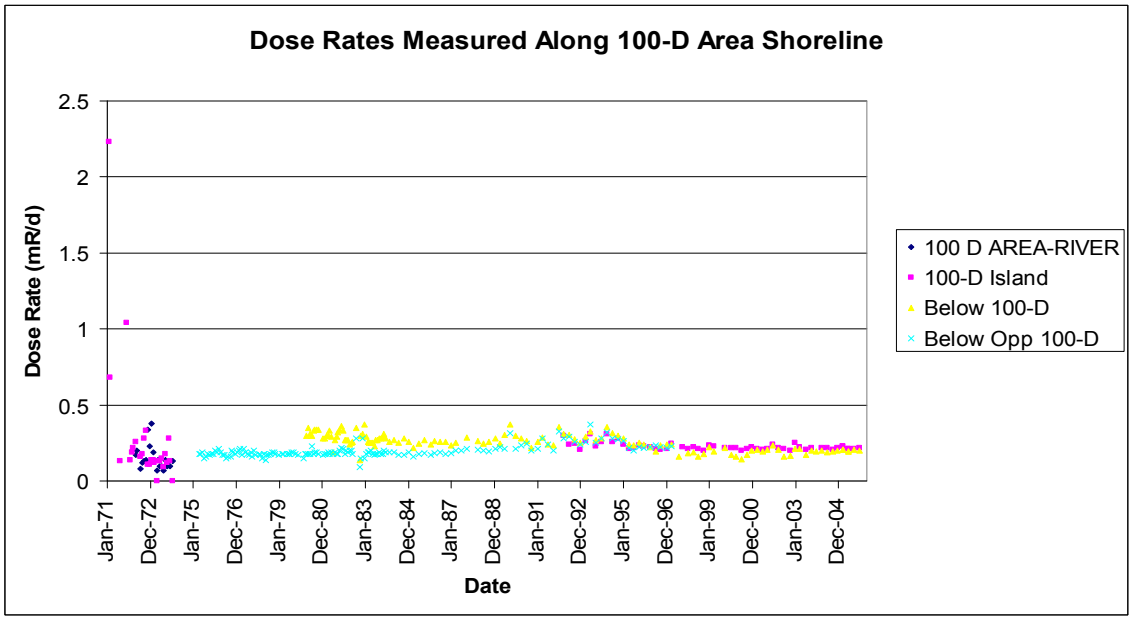


Figure B.17. Dose Rates for Four Dosimeter Locations Along the 100-D Area Shoreline, on D Island, and Downstream of 100-D on the Franklin County Side of the River. D Reactor operated from December 1944 through June 1967 and DR reactor operated from October 1950 through December 1964. This is a composite of the data contained in Figure B.18 through B.21.

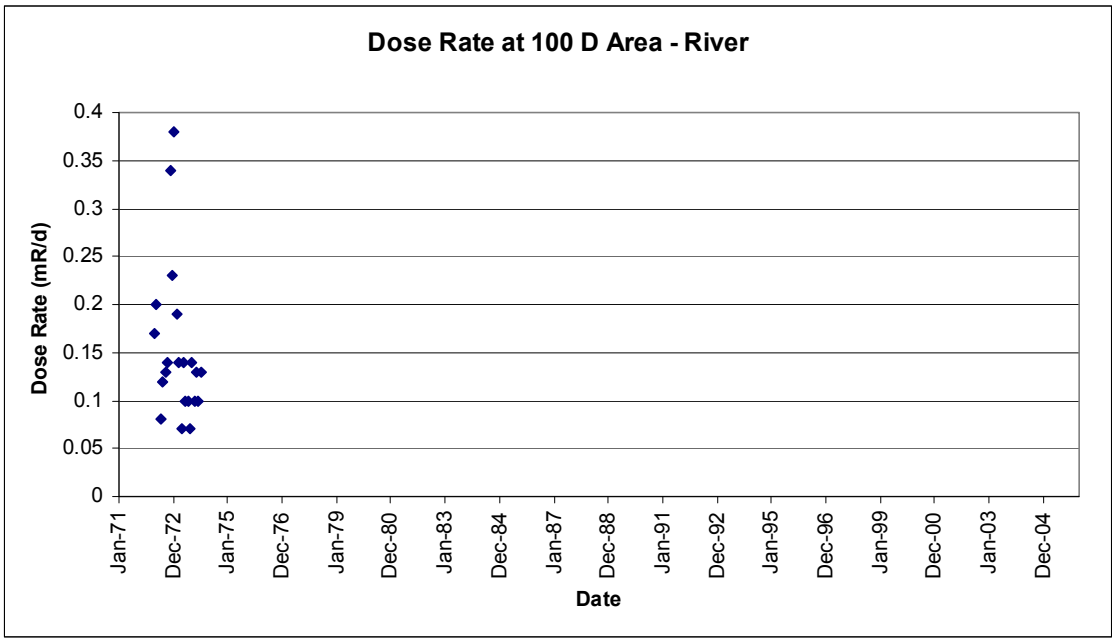


Figure B.18. Dose Rates Were Measured at the 100-D Area River Location from March 1972 Through January 1974. No specific location found.

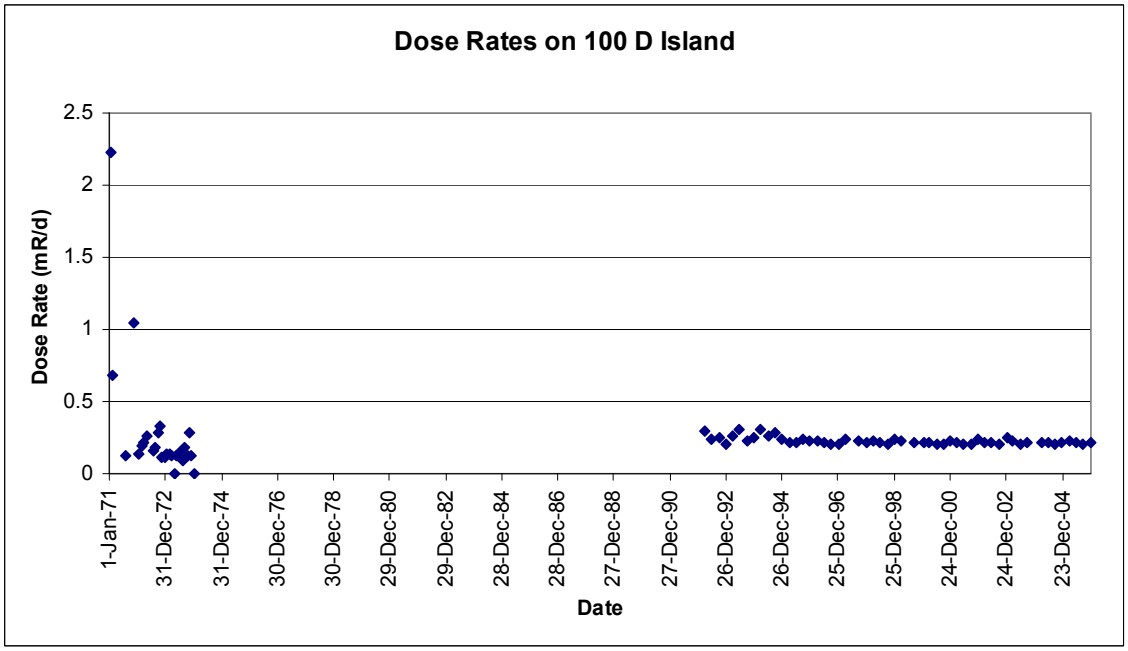


Figure B.19. Dose Rates Were Measured on 100-D Island from January 1971 Through January 1974, Then Resumed in January 1992 and Continued Through December 2005. The dosimeter locations for the two sampling periods were not in the exact same location. No record was found on the location during the early sampling period. During the later sampling period, the dosimeter was located on the upstream end of the island. Sula (1980) measured a maximum exposure rate of 125 µR/h on D Island, while Cooper and Woodruff (1993) measured a maximum of 11 µR/h. Average exposure rates on the island were 9 µR/h and 10 µR/h, respectively.

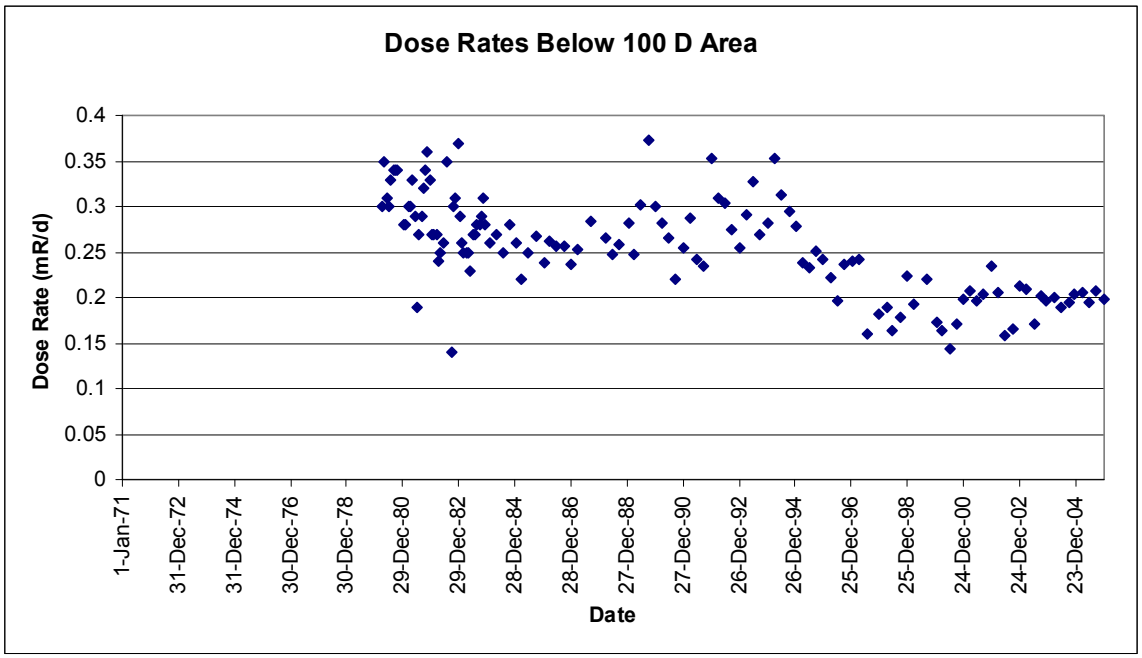


Figure B.20. Dose Rates Were Measured Below 100-D Area from March 1980 Through December 2005. The dosimeter was located downstream of the 100-D Area, approximately 150 feet upstream of the 100-D Area outfall.

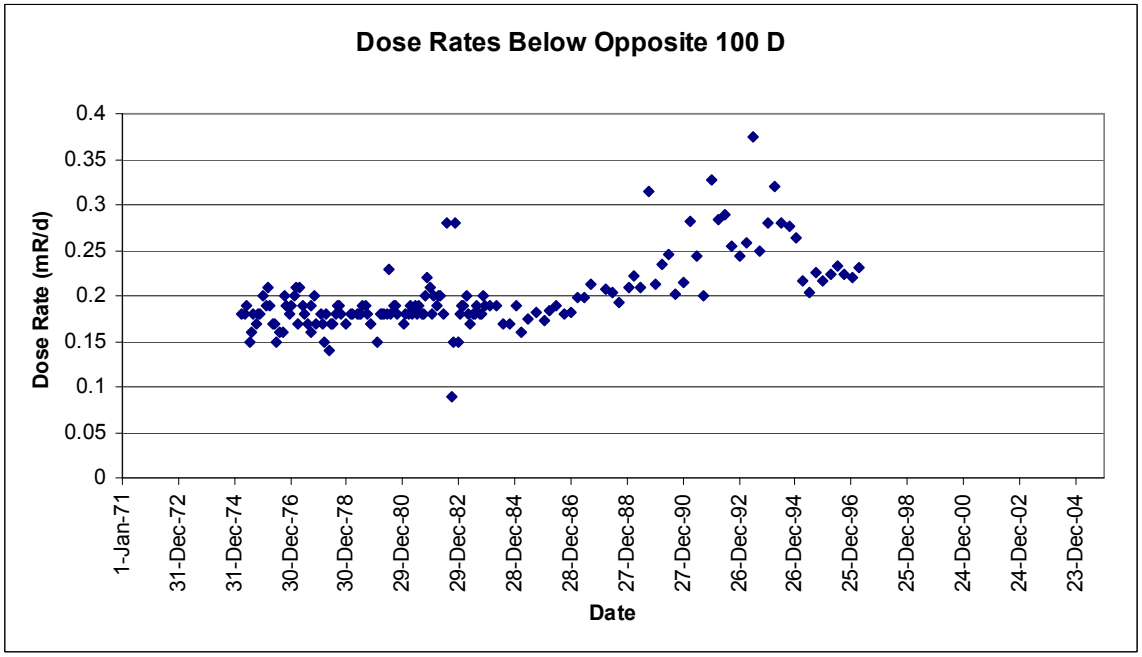


Figure B.21. Dose Rates Were Measured at Below Opposite 100-D Area from March 1975 Through March 1997. The dosimeter was located on the Franklin County side of the river, just downstream of the 100-D Area.

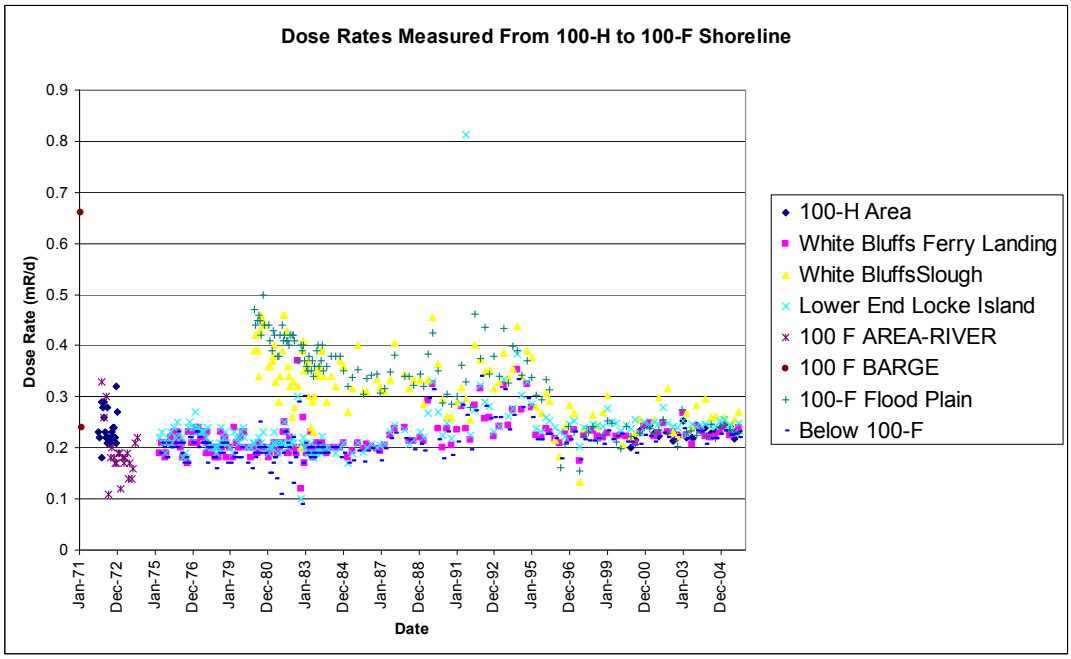


Figure B.22. Dosimeter Results from Eight Shoreline Locations from the 100-H Area Downstream to the 100-F Flood Plain. H Reactor operated from October 1949 through April 1965 and F Reactor operated from February 1945 through June 1965. This is a composite of the data contained in Figures B.23 through B.30.

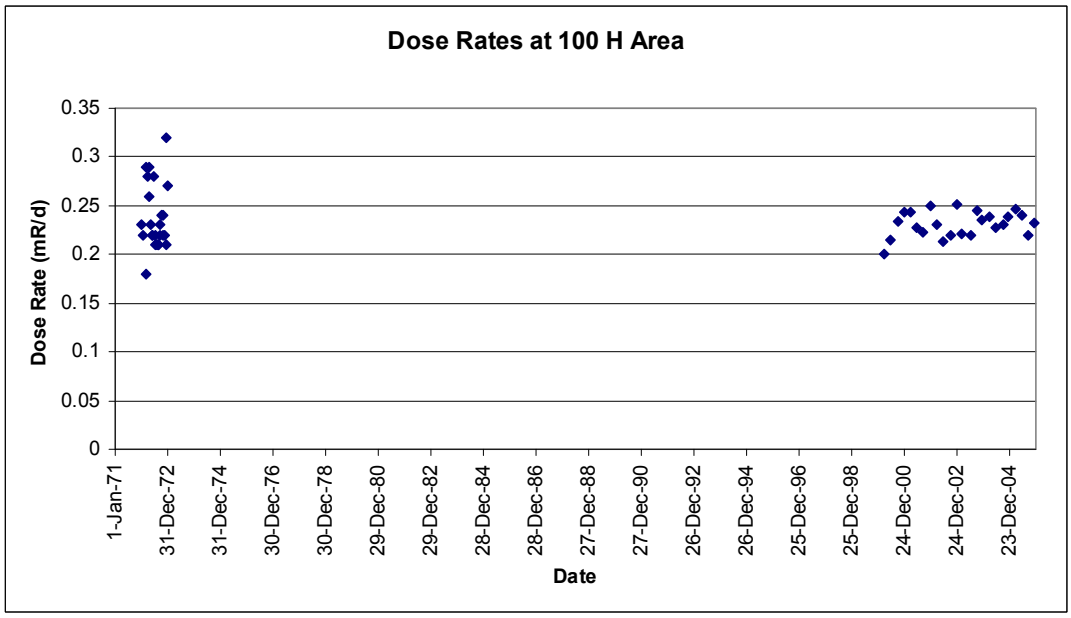


Figure B.23. Dose Rates Were Measured at the 100-H Location from January 1972 Through December 1972, Then Resumed in January 2000 and Continued Through December 2005. The dosimeter positions were not the same during the two time periods. The location of the dosimeter from 2000 through 2005 was along the shoreline at 100-H Area near stone steps leading down to the river.

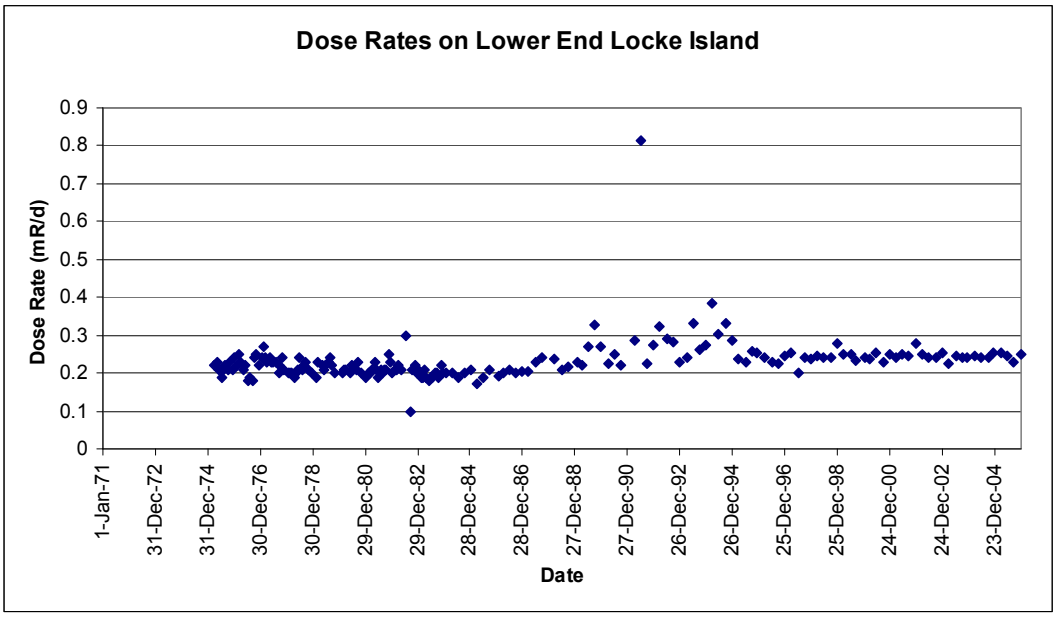


Figure B.24. Dose Rates Were Measured at the Lower End of Locke Island from March 1975 Through December 2005. The dosimeter was located on the downstream end of Locke Island (Island 372), on the Hanford side of the tip. Sula (1980) measured a maximum exposure rate of 25 µR/h on the upper end of Locke Island and 18 µR/h on the lower end. Cooper and Woodruff (1993) measured a maximum of 15 µR/h on the island. No comment was found in the annual report regarding the elevated dose rate measured in the second quarter of 1991.

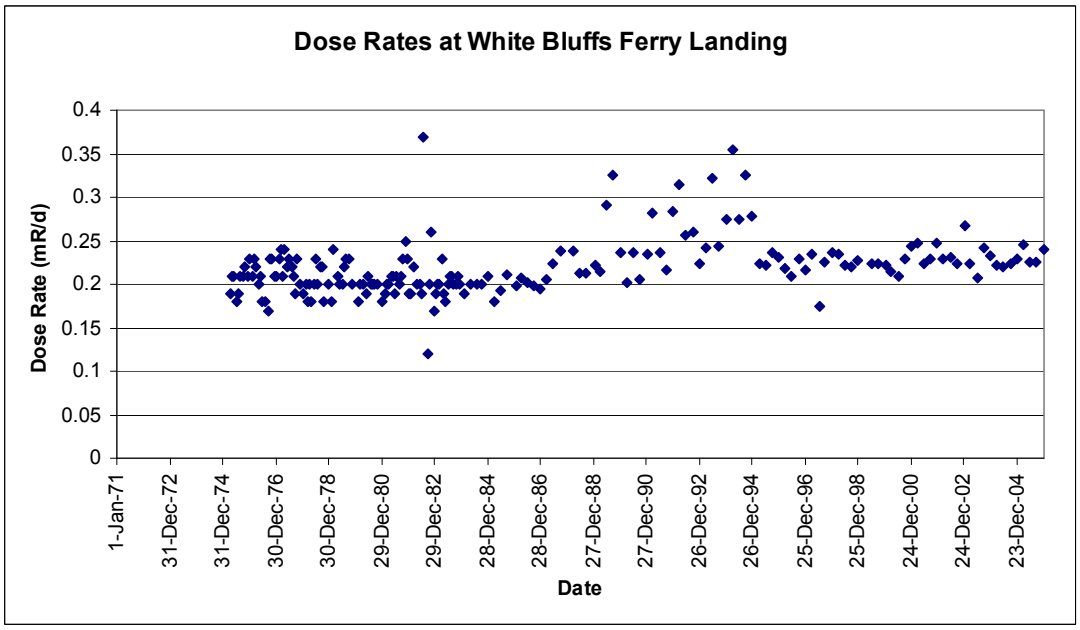


Figure B.25. Dose Rates Were Measured at the White Bluffs Ferry Landing from March 1975 Through December 2005. The dosimeter was located on the Benton County side of the river at the old township of White Bluffs. The TLD was located approximately 100 feet south of a concrete boat launch or ferry landing going into the river.

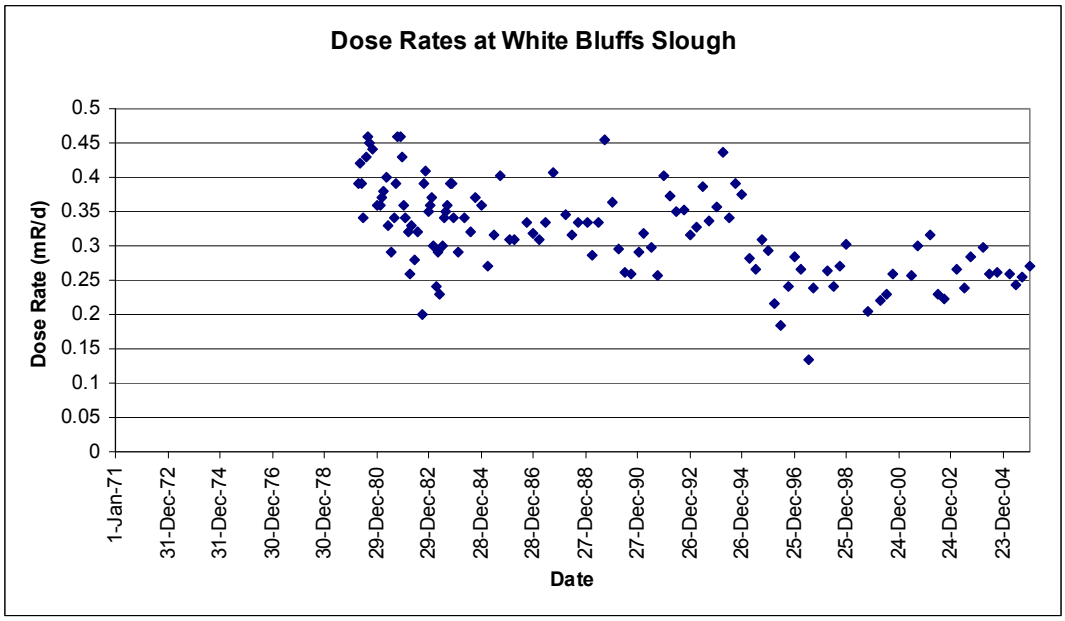


Figure B.26. Dose Rates Were Measured in the White Bluffs Slough from March 1980 Through December 2005. The dosimeter was located approximately 0.3 mile upstream from the White Bluffs Ferry Landing and approximately 20 feet from shore at normal river levels. Discrete particles of cobalt-60 have been found in the slough (Sula 1980) and Cooper and Woodruff (1993) identified slightly elevated levels of sodium-22, cesium-137, europium-152, and plutonium-239/240 in sediment samples. A maximum exposure rate of 28 µR/h was recorded in the slough, with an average of 20 µR/h (Cooper and Woodruff 1993).

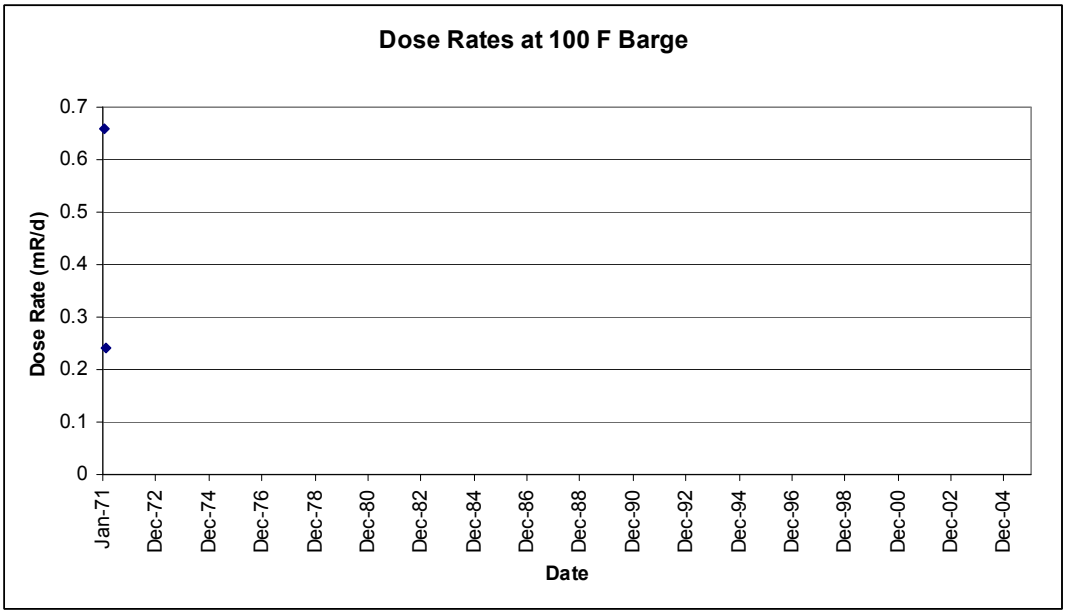


Figure B.27. Dose Rates Were Measured at 100-F Barge from December 1970 to February 1971. The barge was positioned over the water outfall pipe. No mention was found in the 1971 status report (Bramson and Corley 1972a) or in the surveillance report (Bramson and Corley 1972b).

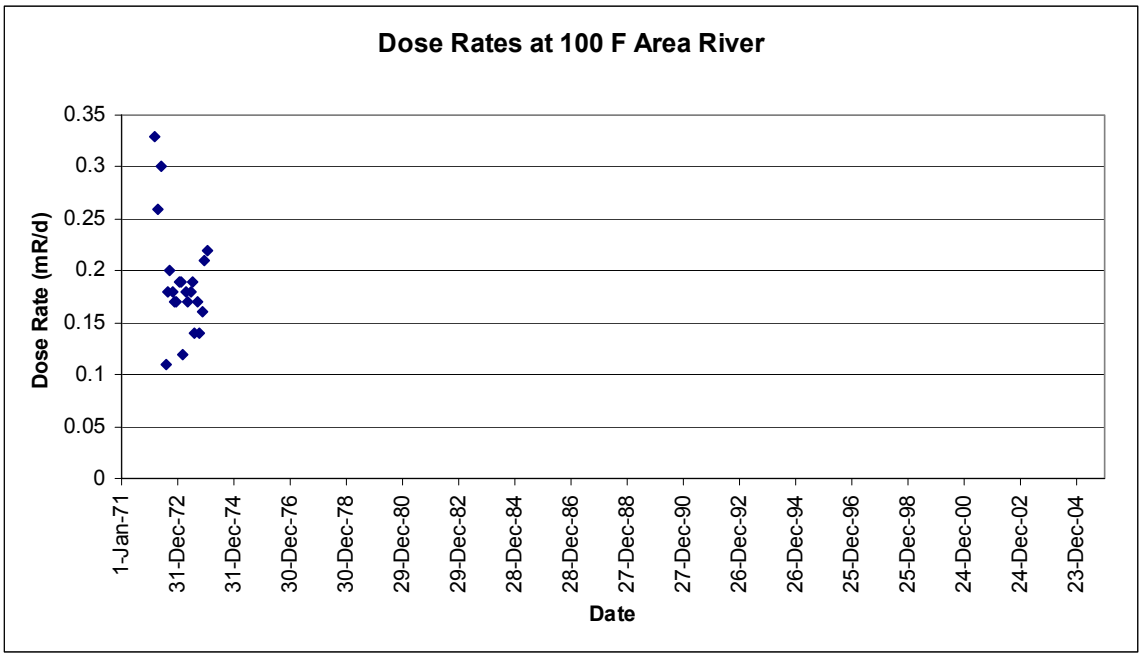


Figure B.28. Dose Rates Were Measured at 100-F Area River from March 1972 Through January 1974. The dosimeter at this location may have been submerged in the Columbia River.

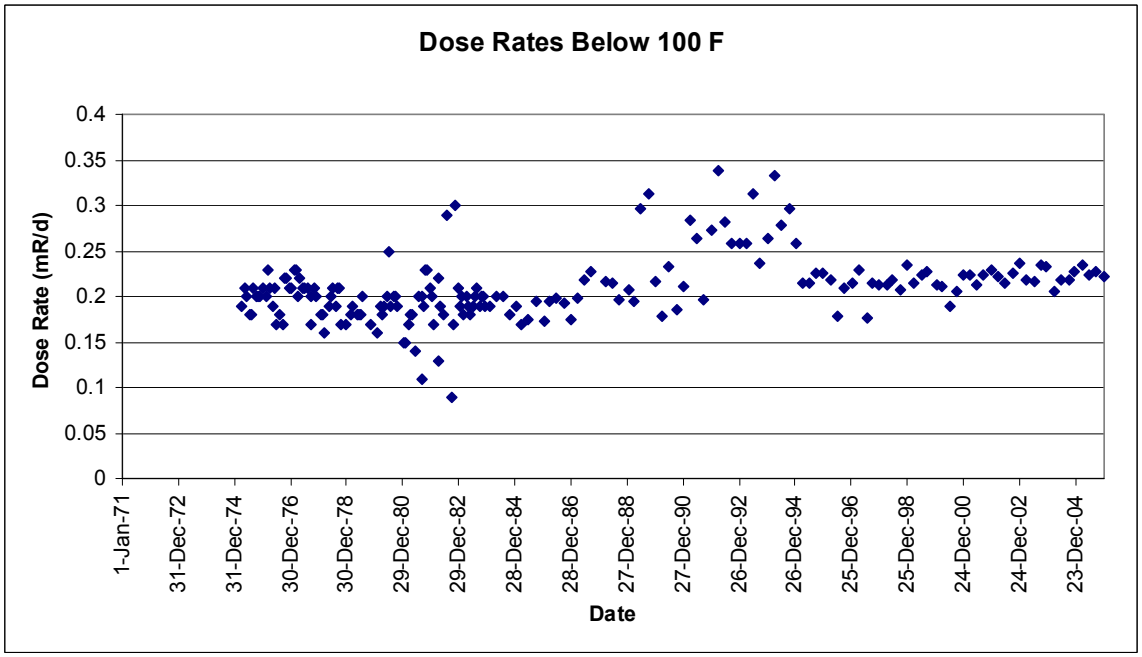


Figure B.29. Dose Rates Were Measured Below the 100-F Area from March 1975 Through December 2005. The dosimeter was located on the Hanford shoreline near river mile marker 19.

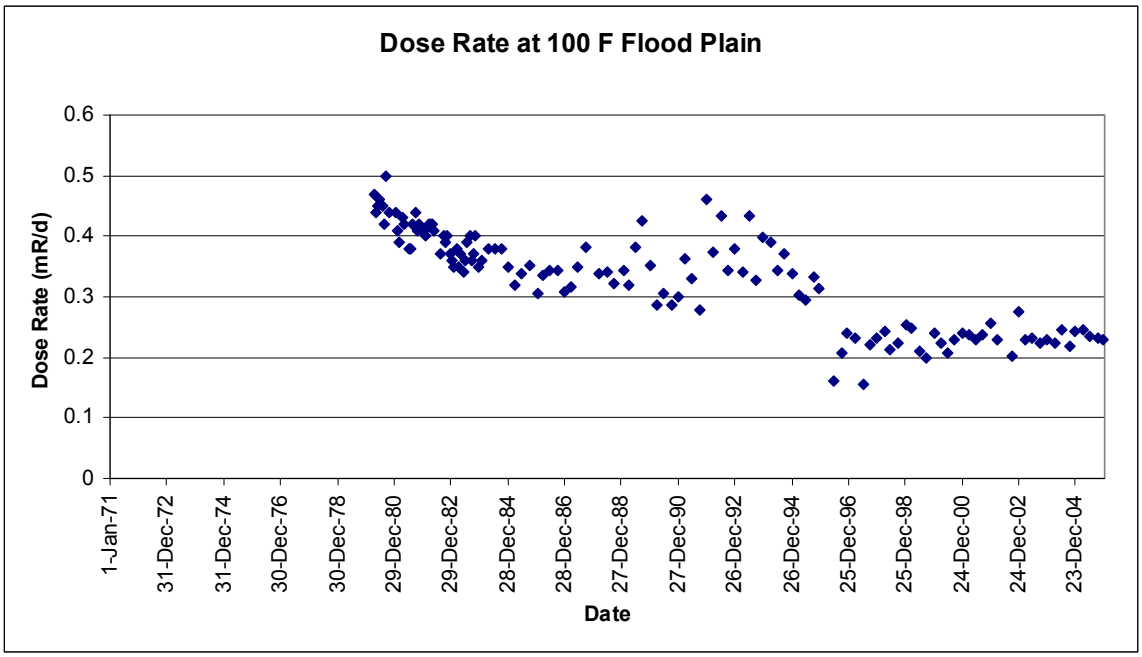


Figure B.30. Dose Rates Were Measured on the 100-F Flood Plain from April 1980 Through December 2005. The dosimeter was located on the flood plain downstream from the river mile marker 19. Sula (1980) found 10 discrete hot particles on the flood plain and measured a maximum exposure rate of 31 µR/h and an average of 11 µR/h. Cooper and Woodruff (1993) measured a maximum exposure rate of 16 µR/h on the flood plain.

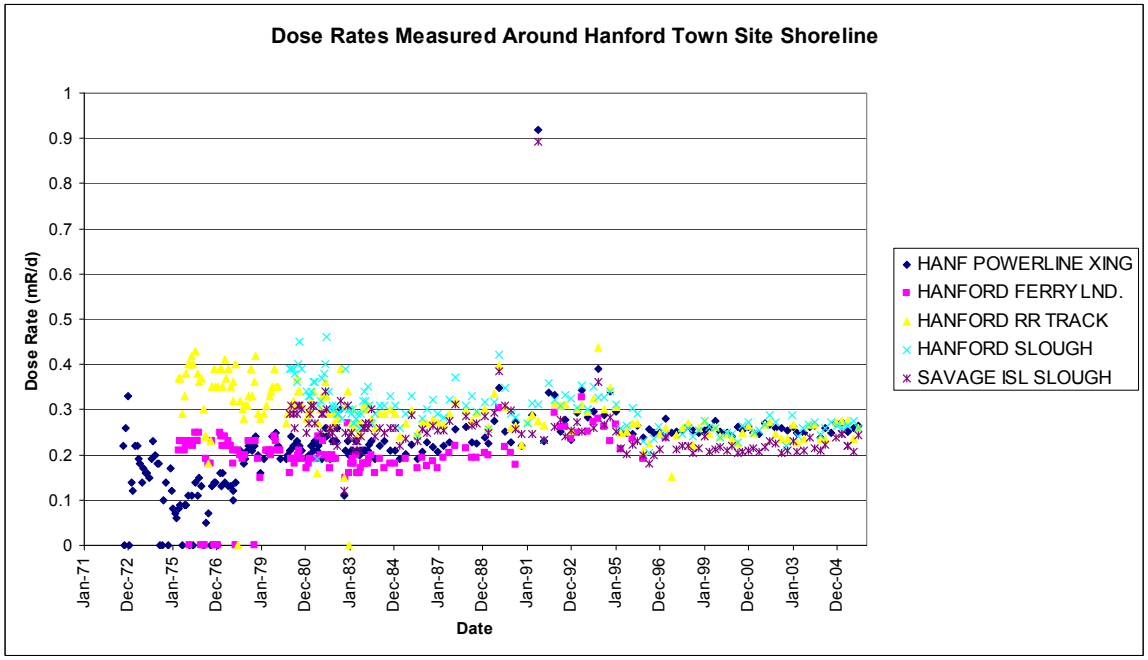


Figure B.31. Dose Rates at Dosimeter Locations Surrounding the Hanford Townsite Shoreline. This is a composite of data contained in Figures B.32 through B.36.

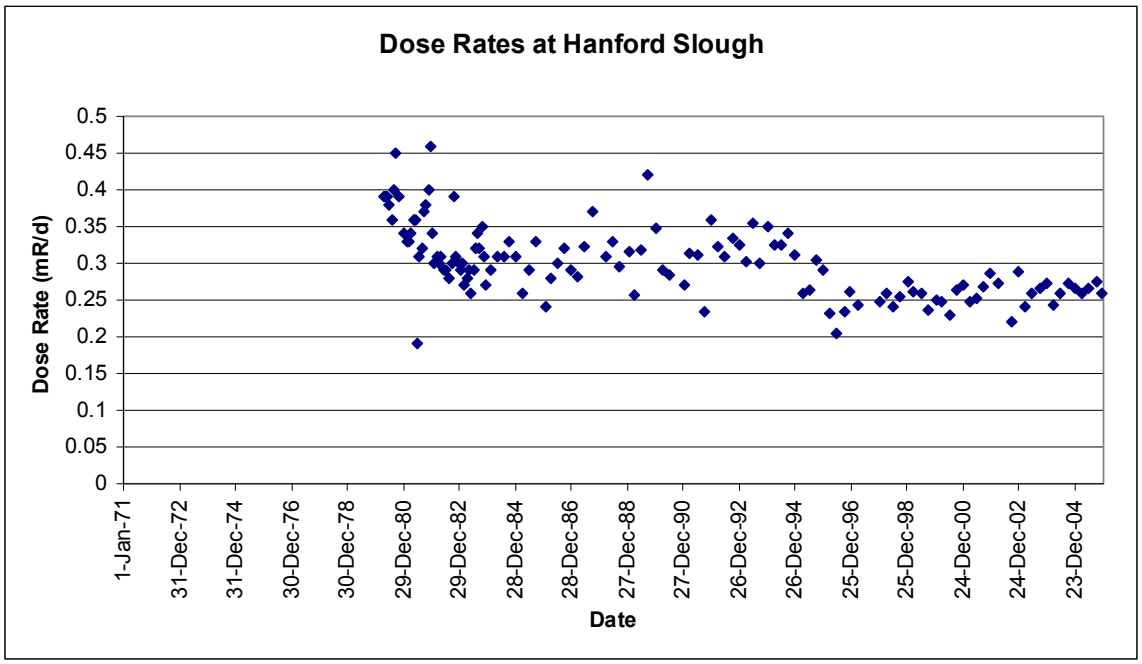


Figure B.32. Dose Rates Were Measured at Hanford Slough from April 1980 Through December 2005. The dosimeter was located near the high-water mark in the Hanford slough, approximately 0.3 mile from Route 2N.

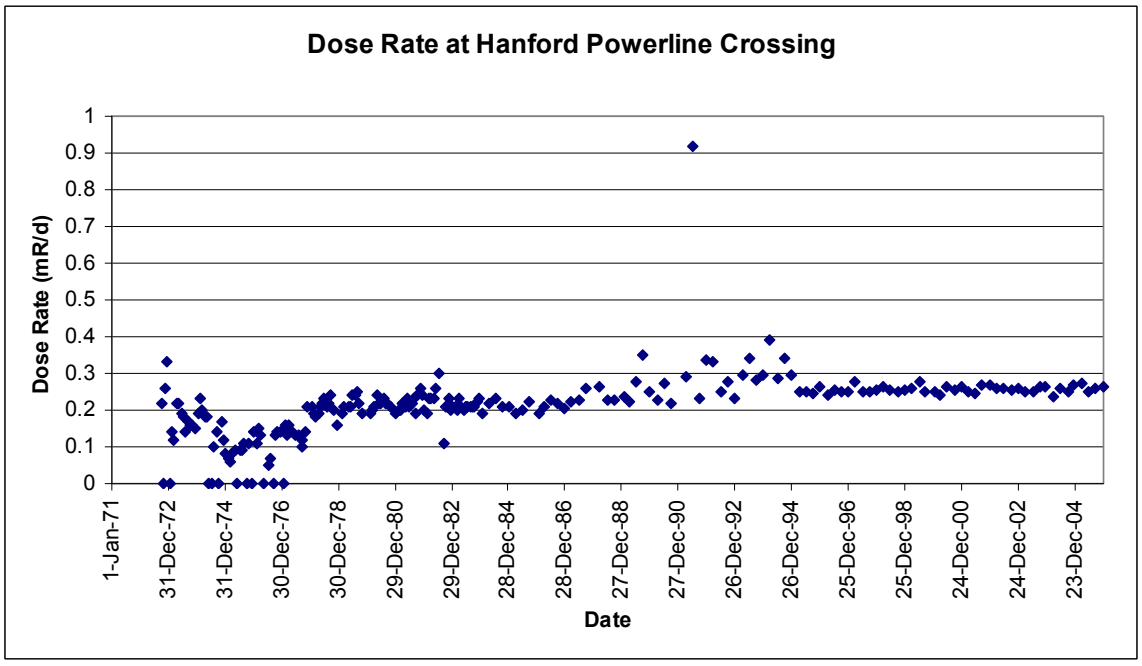


Figure B.33. Dose Rates Were Measured at the Hanford Power Line Crossing from October 1972 Through December 2005. The dosimeter was located on the peninsula extending into the river at the Hanford town site, upstream of the power lines crossing the Columbia River. No comment was made in the annual report regarding the elevated dose rate in June 1991.

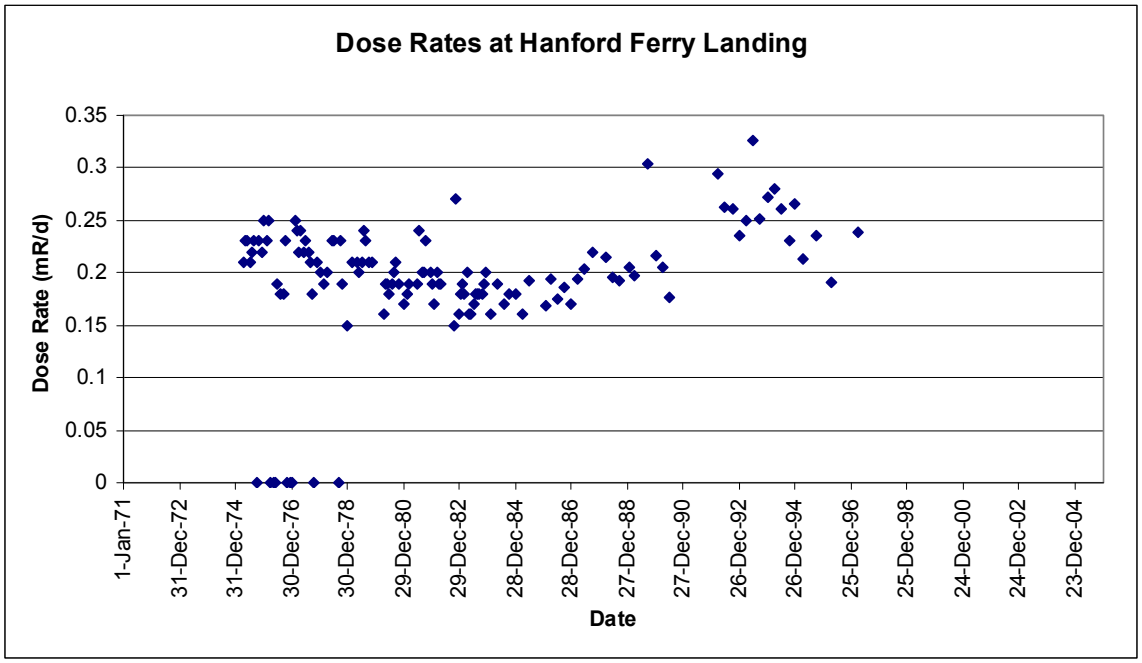


Figure B.34. Dose Rates Were Measured at the Hanford Ferry Landing from March 1975 Through March 1997. The dosimeter was located on the Franklin County side of the Columbia River on the upstream side of a muddy cove where the old Hanford ferry used to land. All TLDs deployed at this site in 1991 were stolen.

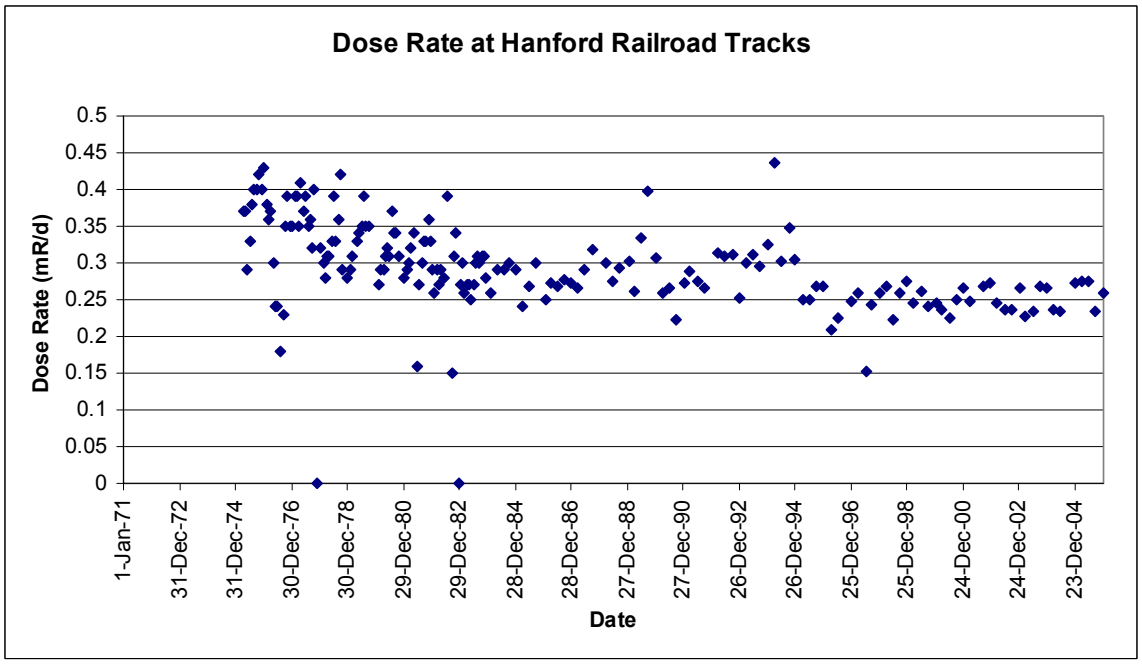


Figure B.35. Dose Rates Were Measured at Hanford Railroad Tracks from March 1975 Through December 2005. The dosimeter was located on the Hanford shoreline approximately 200 meters downstream of the river mile marker 26.

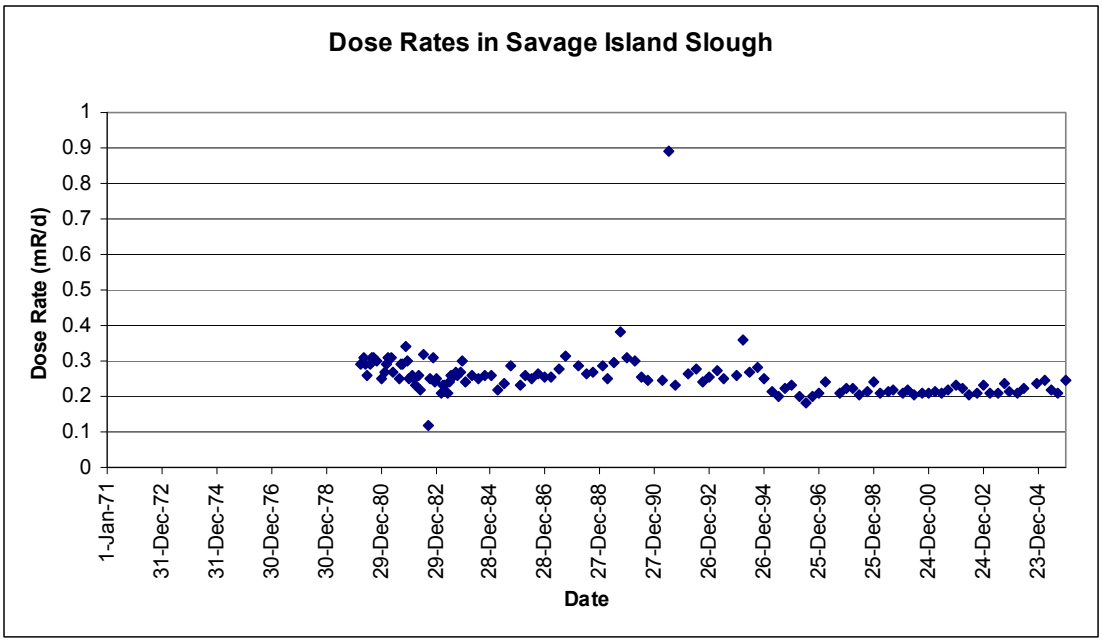


Figure B.36. Dose Rates Were Measured at Savage Island Slough from April 1980 Through December 2005. The dosimeter was located approximately 2 miles downstream from the Hanford townsite on the Franklin County side of the river, approximately 100 meters downstream of the brush gully that becomes filled with water during high-water periods. No comments were found regarding the elevated result reported for second quarter 1991. Sula (1980) measured a maximum exposure rate of 24 µR/h in the slough and an average of 11 µR/h on the island. Cooper and Woodruff (1993) measured a maximum exposure rate of 18.5 µR/h in the slough and an average of 15.2 µR/h on the shoreline.

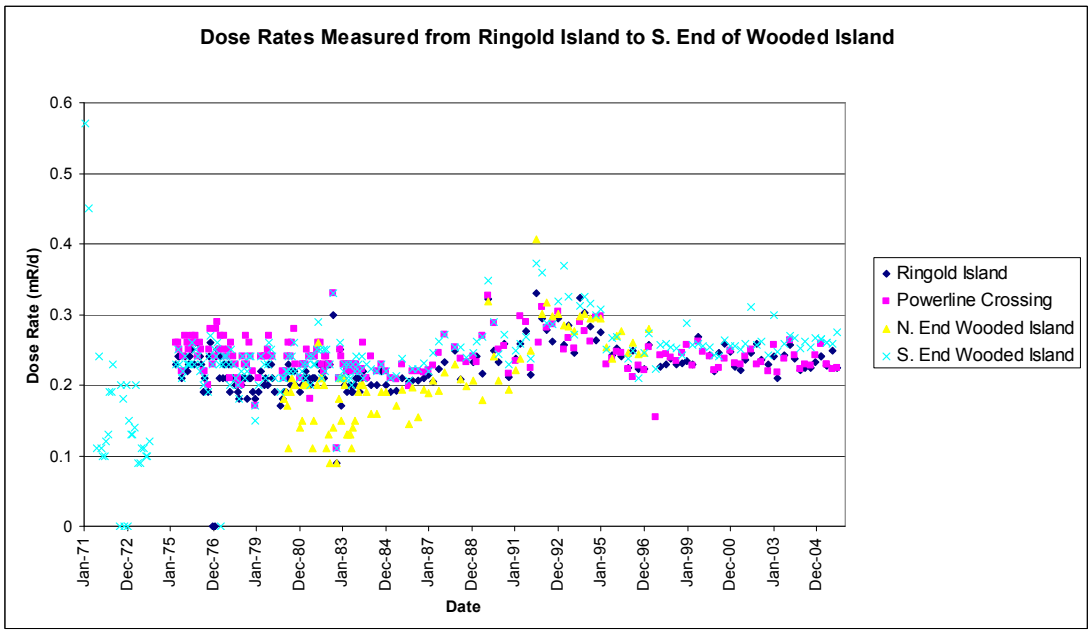


Figure B.37. Dose Rates Measured for the Stretch of Columbia River Beginning at Ringold Downstream to the South End of Wooded Island (Island 348). This is a composite of data contained in Figure B.38 through B.41.

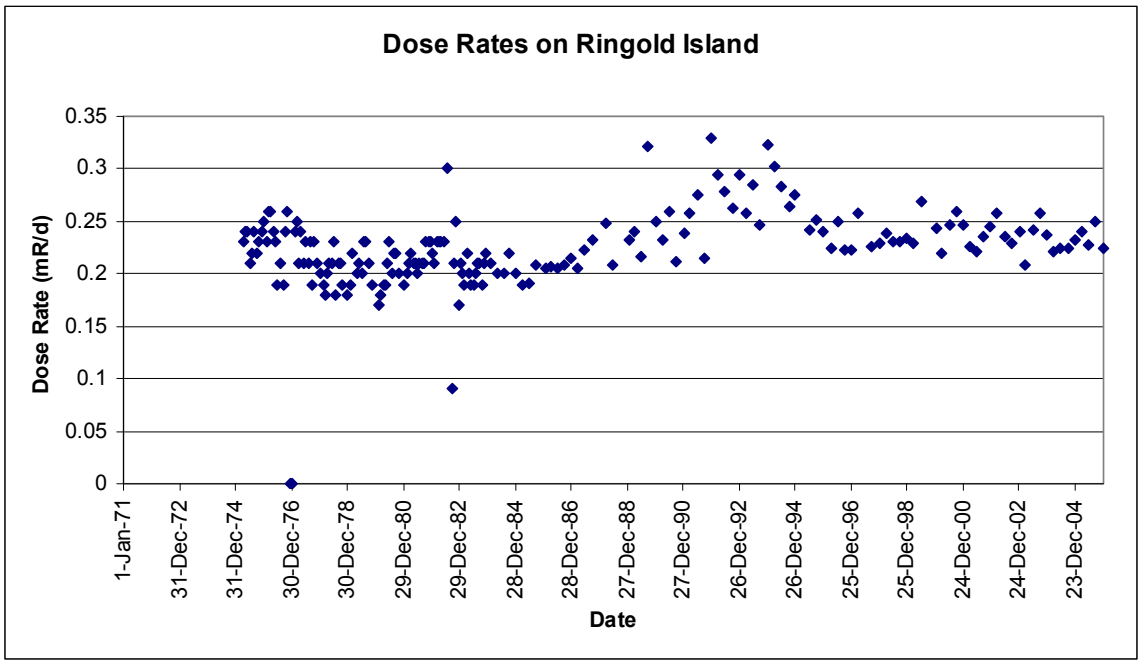


Figure B.38. Dose Rates Were Measured on Ringold Island from March 1975 Through December 2005. The dosimeter was located on Ringold Island (Island 355) near the highest point on the downstream end of the island.

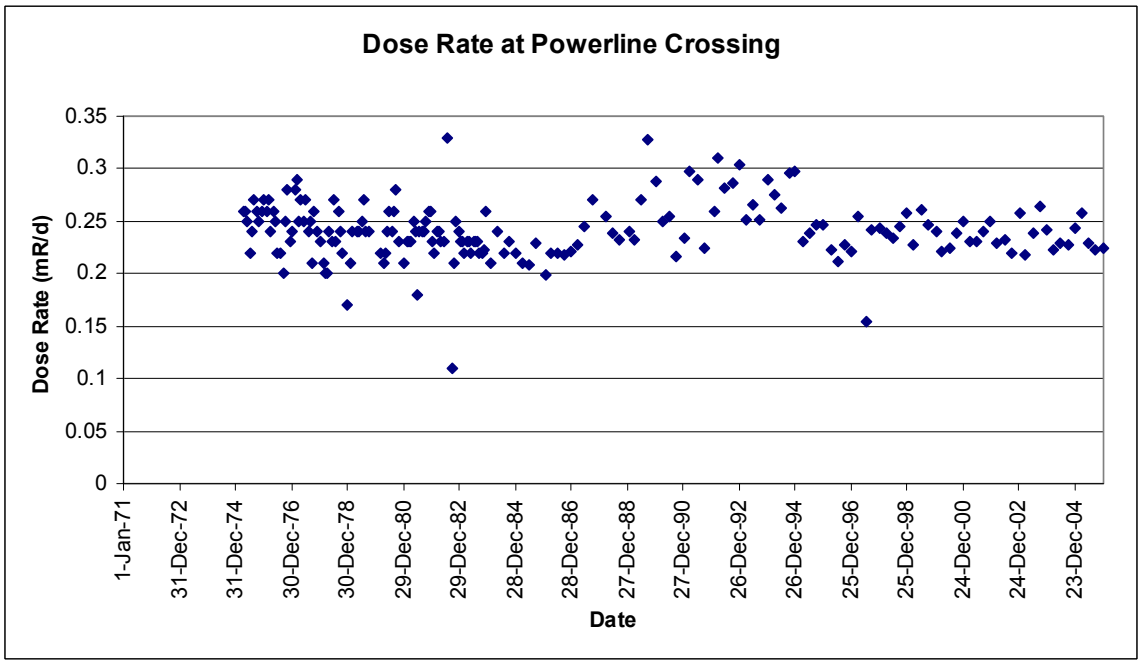


Figure B.39. Dose Rates Were Measured at the Powerline Crossing from March 1975 Through December 2005. The dosimeter was located upstream of the powerlines suspended on large red steel towers spanning the Columbia River between river mile markers 36 and 37.

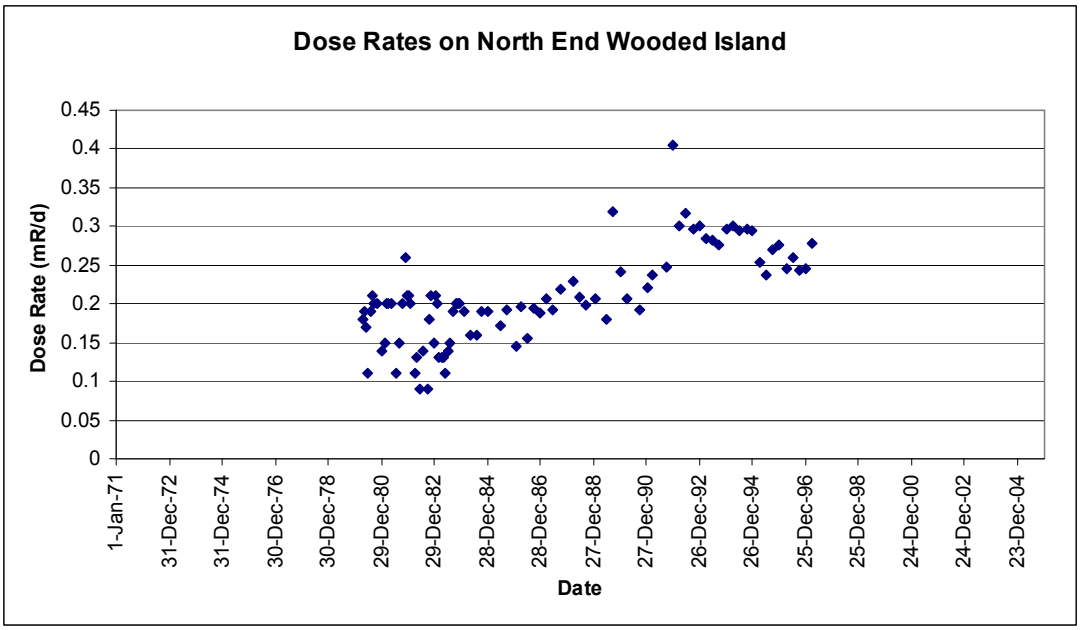


Figure B.40. Dose Rates Were Measured on the North End of Wooded Island from April 1980 Through March 1997. Sula (1980) measured a maximum exposure rate of 15 µR/h and an average of 10 µR/h on the north end of Wooded Island. Cooper and Woodruff (1993) measured a maximum of 15 µR/h and an average of 14.3 µR/h on the upper end of Wooded Island. No comment was found regarding the elevated reading from December 1991.

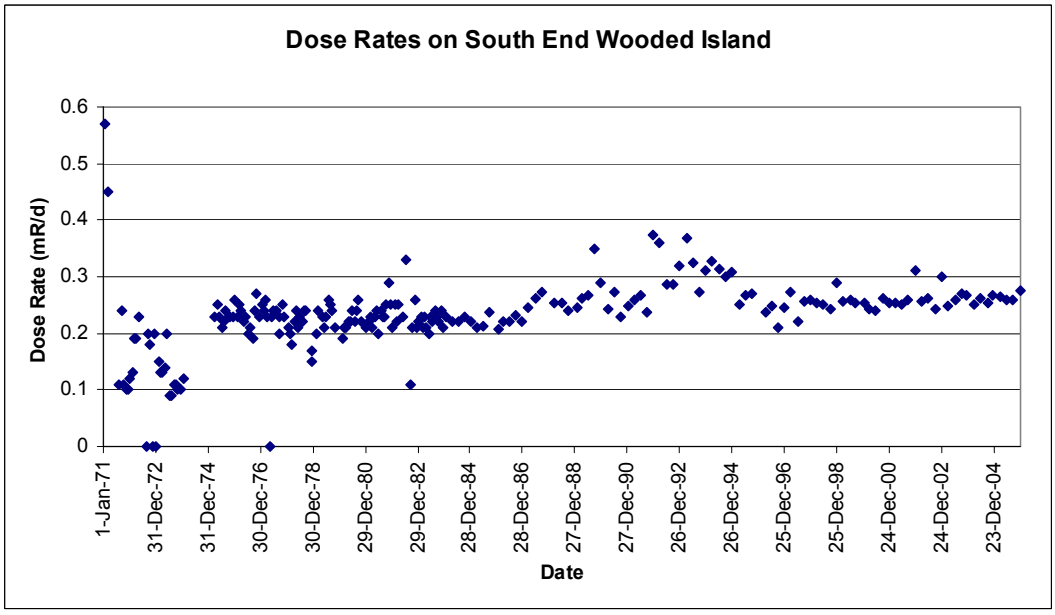


Figure B.41. Dose Rates Were Measured on the South End of Wooded Island from January 1971 Through December 2005. From the Columbia Generating Station powerline crossing, the dosimeter on the south end of Wooded Island is approximately 2.5 miles downstream and is located on the Franklin County side of the island, on a bank about 1 meter high. The elevated exposure rates measured in 1971 may have been measured with pencil dosimeters, rather than TLDs.

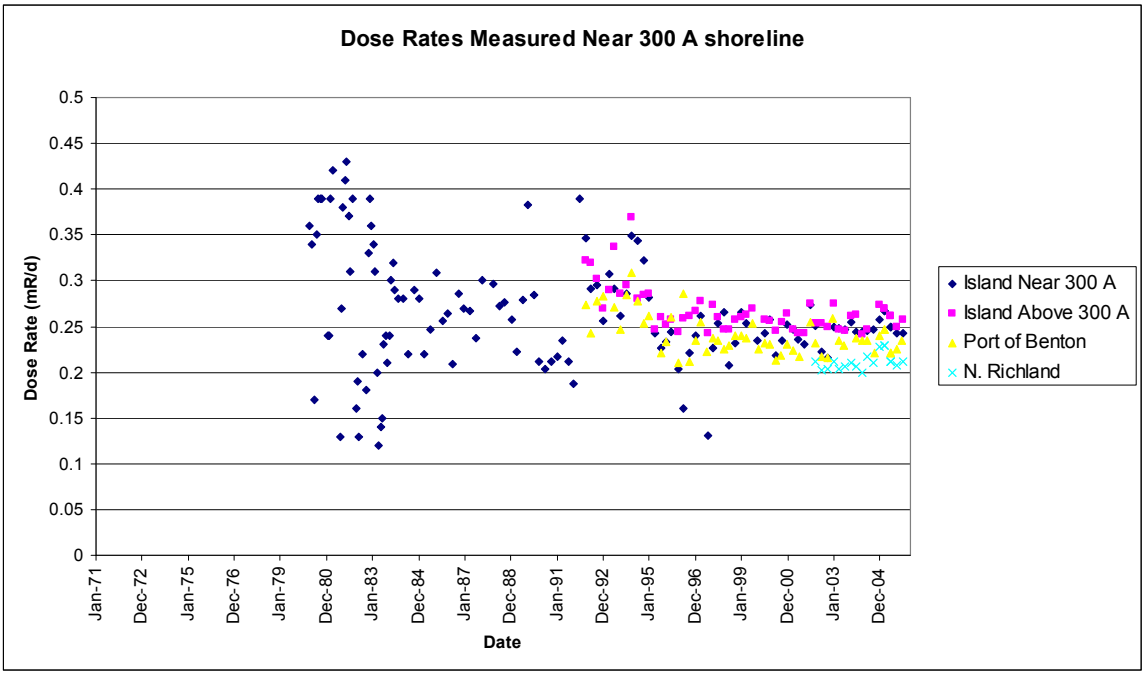


Figure B.42. Collective Results from TLD Measurements Taken Along the Columbia River Shoreline Around the Hanford Site's 300 Area and Downstream to North Richland. This is a composite of the data contained in Figures B.43 through B.46.

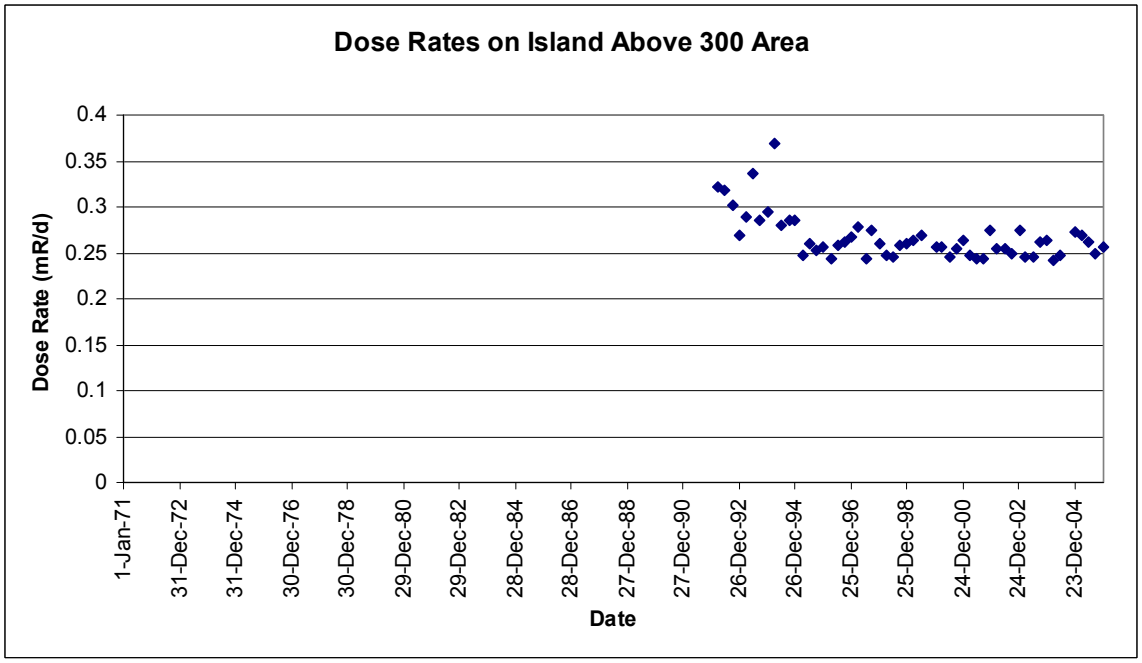


Figure B.43. Dose Rates Were Measured on the Island Just Upstream of the 300 Area from January 1991 Through December 2005. The dosimeter was located on the east side of the island near the downstream end.

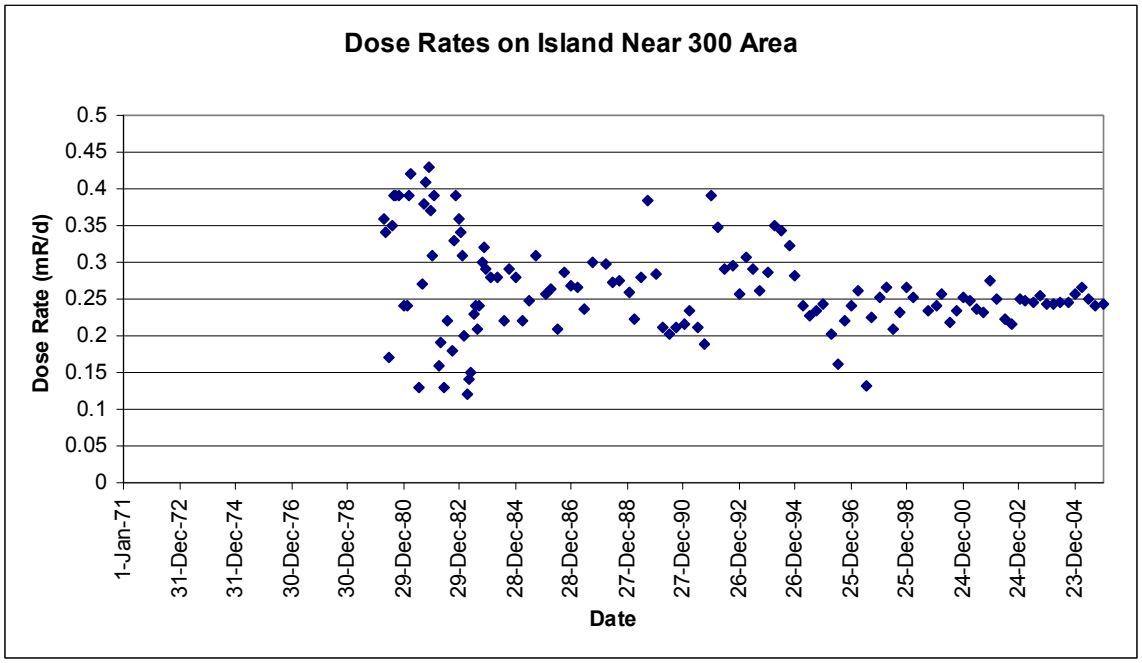


Figure B.44. Dose Rates Were Measured on the Island Near the 300 Area from April 1980 Through December 2005. The dosimeter was located approximately 6 miles upstream from the boat launch at Leslie Groves Park in Richland. It is on the Franklin County side of the island in front of the 300 Area at about Hanford river mile marker 43.

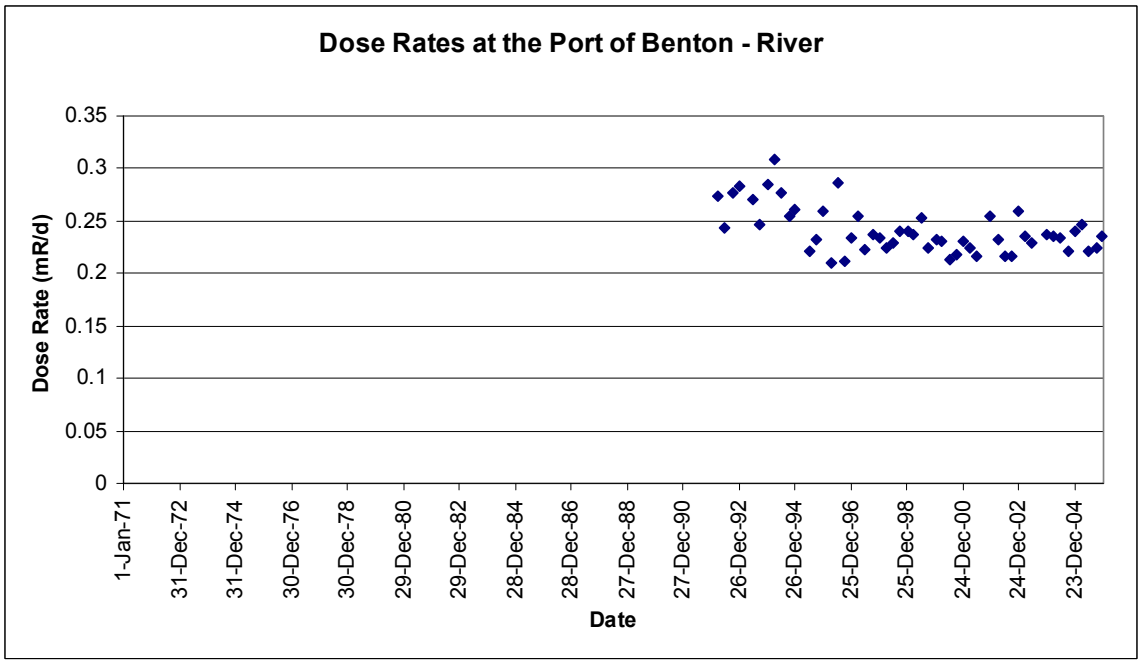


Figure B.45. Dose Rates Were Measured at the Port of Benton from January 1992 Through December 2005. The dosimeter was located approximately 50 meters upstream of Hanford river mile marker 44.

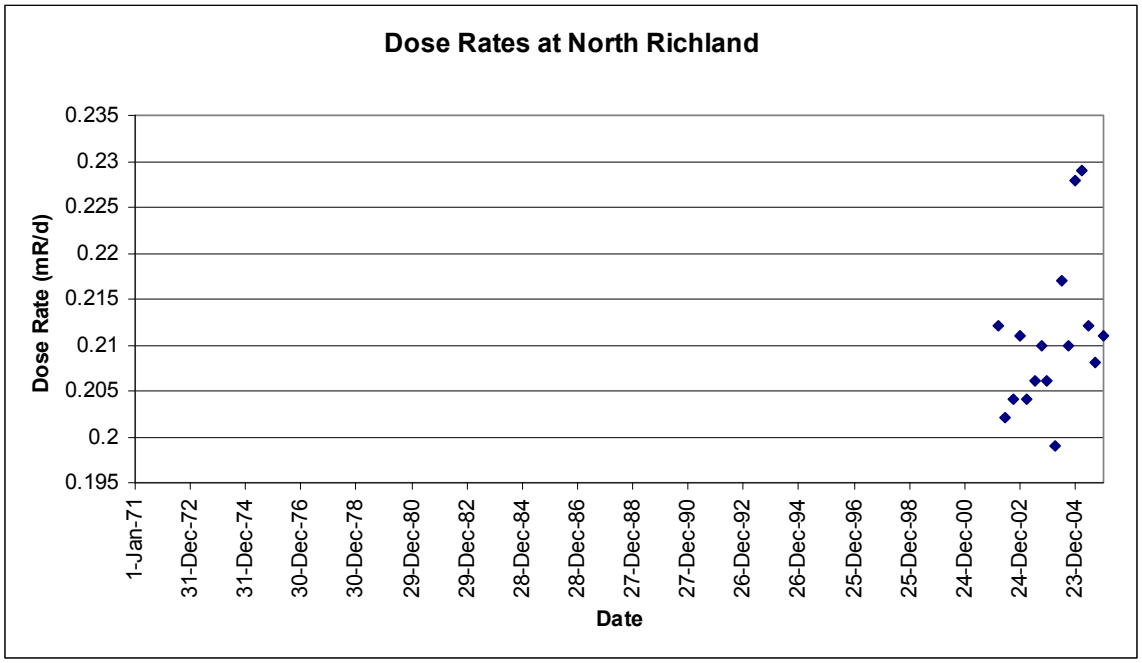


Figure B.46. Dose Rates Were Measured at the North Richland Location from January 2002 Through December 2005. It was established to replace the dosimeter location at Leslie Groves Park (perimeter location) due to continued vandalism of the TLD at that location. It was situated on the shoreline, near a private dock of a house with a green metal roof.

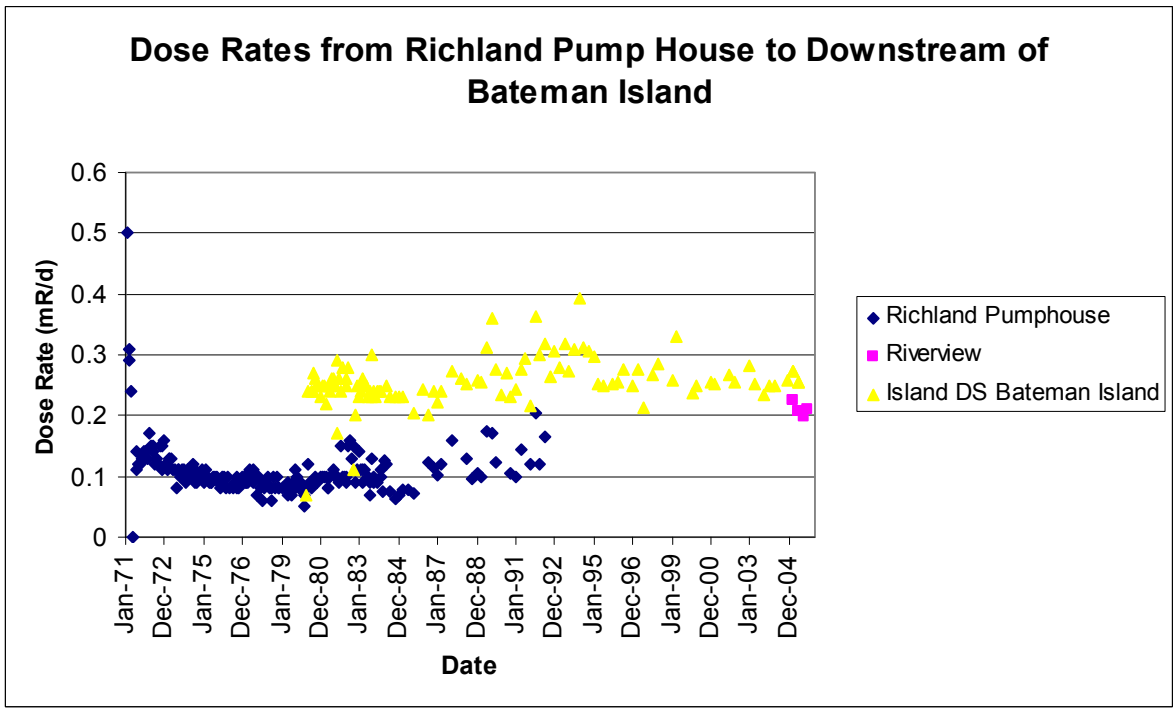


Figure B.47. Shoreline Dose Rates Measured Along the Columbia River from the Richland Pumphouse Downstream to the Island Downstream of Bateman Island. This is a composite of the data contained in Figures B.48 through B.50.

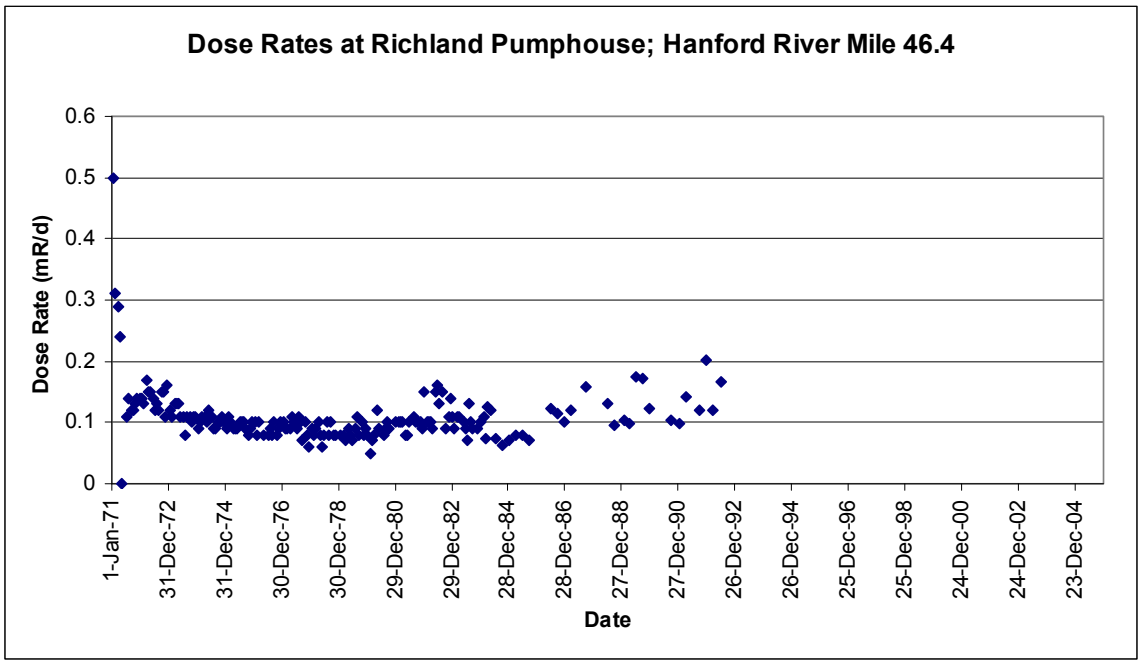


Figure B.48. Dose Rates Were Measured at the Richland Pump House from January 1971 Through June 1992. The dosimeter was located at Hanford river mile 46.4, at the City of Richland water intake structure, below the water surface of the river.

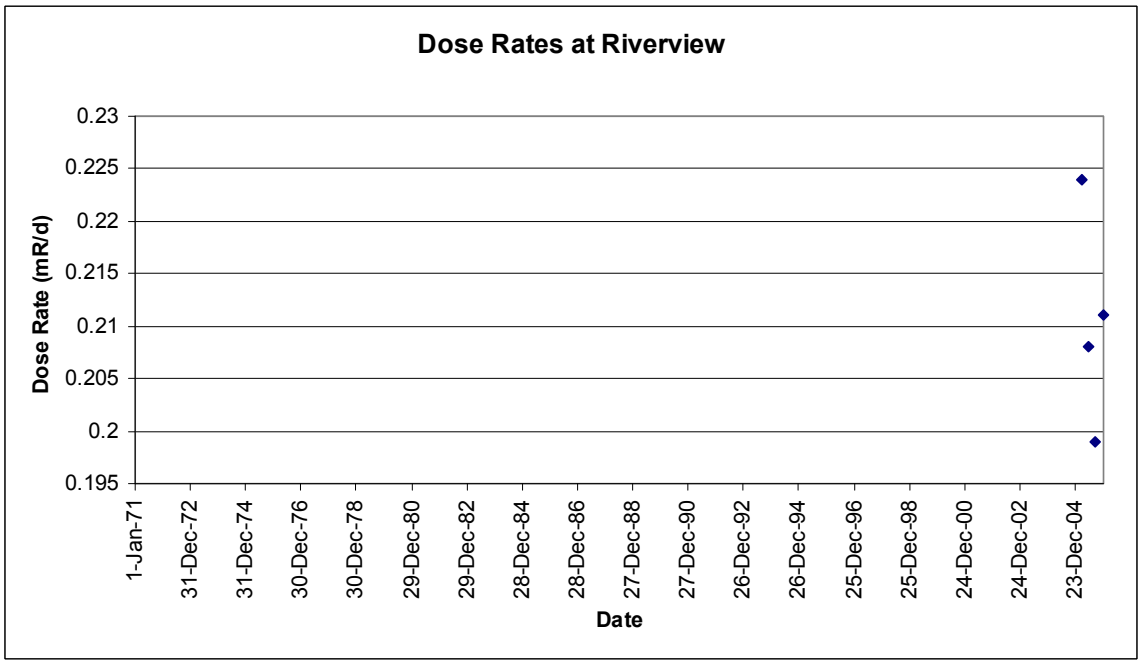


Figure B.49. Dose Rates at Riverview Were Only Measured During 2005. The dosimeter was established to replace the continually vandalized dosimeter located on a downstream island. The dosimeter was located on the Franklin County shoreline and across the river from the mouth of the Yakima River.

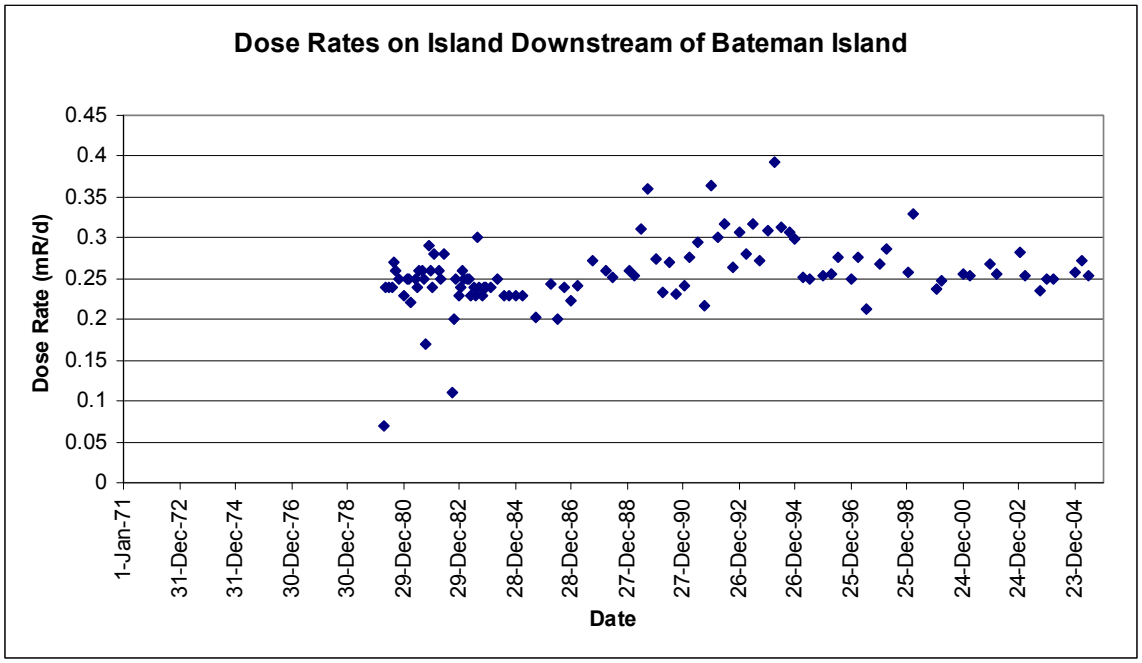


Figure B.50. Dose Rates Were Measured on the Island Just Downstream from Bateman Island from April 1980 Through December 2005. The dosimeter was located on the Benton County side of the island directly downstream of Bateman Island, about halfway down the island and just inland from channel marker number 54.

B.2 References

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Appendix C

Overview of Production Reactor Operations and Facilities at Hanford

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Overview of Production Reactor Operations and Facilities at Hanford

This appendix briefly reviews the facilities and operations that supported the plutonium production mission at the Hanford Site. This information is included to provide a perspective of the complexity of operations conducted at Hanford and as background material for the operations that produced or involved the handling of radioactive materials. The eight tables in this appendix include the years of operation of these facilities, some of which operated before full implementation of the Hanford Environmental Surveillance Thermoluminescent Dosimeter (TLD) Program in the early 1970s. A more comprehensive discussion of these operations can be found in the report by Harvey (2003).

C.1 Plutonium Production Reactor Operation

The only Hanford plutonium production reactors that operated during the timeframe when TLDs were used were the 100-K East (KE) and N reactors (Table C.1). N Reactor (the ninth production reactor at Hanford) was a dual-purpose reactor that produced both plutonium and steam used to generate electrical power. The reactor started producing plutonium in 1964 and electrical power sometime after that. The KE reactor stopped production in January 1971.

Table C.1. Production Reactors Years (month/year) of Operation

B	C	D	Dr	F	H	KE	KW	N
9/1944– 2/1968	11/1952– 4/1969	12/1944– 6/1967	10/1950– 12/1964	2/1945– 6/1965	10/1949– 4/1965	2/1955– 1/1971	12/1954– 2/1970	12/1963– 1/1987

C.1.1 Research and Test Reactor Operation

The only research and test reactors that operated during the timeframe that TLDs were used were the Hanford Test Reactor (HTR), the Thermal Test Reactor (TTR), the Plutonium Recycle Critical Facility (PRCF), and the Fast Flux Test Facility (FFTF) (Table C.2). The Physical Constants Test Reactor (PCTR), the Plutonium Recycle Test Reactor (PRTR) and the High Temperature Lattice Test Reactor (HTLTR) were not monitored as part of the surveillance TLD program and are not discussed further.

Table C.2. Research and Test Reactors Years of Operation

Reactor						
HTR	PCTR	TTR	PRTR	PRCF	HTLTR	FFTF
1943–1972	1954–1970	1954–1978	1960–1969	1962–1976	1968–1971	1980–1994

The HTR, also called the Test Pile, was the first reactor to operate at Hanford. It was operated until 1972 at very low critical level (usually less than 50 W) to test fuel elements, fuel configurations, graphite samples, and other material for the production reactors. The reactor consisted of a graphite pile and was air cooled. It was removed from the 305 Building in 1976–1977. No surveillance TLDs were located where they would measure dose rates from normal operations of this facility.

The TTR started operation in 1954. The 1-kW reactor was located in a shielded underground room in the 305-B Building and was operated remotely. It functioned as an early and small version of the HTLTR. Operation was terminated in 1978. No surveillance TLDs were located where they would measure dose rates from normal operations of this facility.

The PRCF was located in the 309 Building and began operating in 1962. Tests were conducted in this facility to determine which geometrical configuration of fissionable materials would work in a reactor. It was shut down in 1976. No surveillance TLDs were located where they would measure dose rates from normal operations of this facility.

The FFTF was a 400-MW sodium-cooled test reactor located in the 405 Building. It started operations in February 1980 in support of the fast breeder reactor program. The FFTF was used to test fuels and materials that would be used in a breeder reactor and to perform long-term testing of reactor components and systems. It also was used for the production of medical isotopes and research on space power systems. The facility was shut down in 1994. TLDs were located at air surveillance stations positioned around this facility.

The operation of these test reactors and those that preceded the implementation of TLD surveillance created small amounts of radioactive waste that were disposed of at waste sites on the Hanford Site. While these facilities (excepting FFTF) were located in the 300 Area beyond the coverage of environmental TLDs, it is possible that their waste streams could contribute to external radiation dose rates at disposal areas and burial grounds.

C.2 Fuel Reprocessing and Fabrication Facilities

The fuel reprocessing facilities that operated during the timeframe of TLD use were the Plutonium-Uranium Extraction (PUREX) facility, the Uranium Oxide (UO_3) facility, and the 225-B facility (Table C.3). These facilities were located in the 200-East or 200-West Areas and produced both low-level and high-level waste streams, as well as low-level atmospheric discharges of radionuclides. The releases have been documented in annual site environmental reports (http://hanford-site.pnl.gov/envreport/) and when deposited on the ground, could have contributed to external radiation doses measured by the TLD surveillance program. External radiation dose rates were monitored at these facilities by the Near-Field Environmental Monitoring Program. The other facilities listed in Table C.3 supported fuel reprocessing and fabrication and additional information can be found in the report by Harvey (2003).

The PUREX facility was started in January 1956. The PUREX process was an organic solvent-extraction process that used tributyl phosphate in kerosene, nitric acid as a salting agent, pulse column contractors, and nitric acid recovery by distillation. The PUREX plant was shut down in June 1972 and restarted in November 1983. During the shutdown, a new process was added to convert plutonium nitrate

to plutonium oxide. It was started up and shutdown several times between 1983 and 1992 with final closure announced in December 1992.

The UO_3 facility was constructed in the 1940s. In 1951, it was converted to process the liquid uranium nitrate solution from U Plant to produce a powdered UO_3 using a calcination process. It was started up in January 1952, shut down in 1972, opened again in 1983 (there were 17 startups and shutdowns between 1984 and 1992 corresponding to activities at PUREX), and was deactivated in the summer of 1993.

The 225-B facility, or the Waste Encapsulation and Storage Facility, is located in the 200-East Area near the 221-B Building. In 1978, as a part of the effort to isolate the longer-lived fission products from high-level waste tanks, the ^{137}Cs and ^{90}Sr solutions were transferred to the 225-B facility from 221-B Building for conversion to a solid, encapsulation, and storage (see Section 2.2.1 of this report for more details). A large amount of encapsulated ^{137}Cs and ^{90}Sr was stored in the 225-B facility as a result of this operation. External exposures that were associated with the high-energy photons and beta particles from the strontium and cesium processed were minimized by remote operation.

Table C.3. Fuel Reprocessing Facilities Years of Operation

Reprocessing Facility								
B Plant	T Plant	REDOX	PUREX	U Plant	UO_3	225-B	C Plant	Tritium
4/1945–10/1952[a]	12/1944–Present[b]	1/1952–12/1967[c]	1/1956–12/1992[d]	3/1952–1/1958	1951–1993[e]	1974–Present	1949–1967[f]	8/1949–1955

(a) In 1968, B Plant started to remove ^{90}Sr and ^{137}Cs from high-level wastes.
(b) T Plant discontinued reprocessing operations in March 1956 and was used as a decontamination facility; the 2706-T Annex was added in 1959.
(c) The 233-S facility located at the Reduction Oxidation (REDOX) plant started operation in 1957 and shut down in 1967.
(d) Closed in 6/72 and reopened in 11/83.
(e) Shut down in 1972 and opened again in 1983 (there were 17 startups and shutdowns between 1984 and 1992).
(f) C plant started operations as a chemical separations pilot plant at in 1952 for REDOX and in 1954 for PUREX ; used again in 1962 as a pilot plant for recovery of cesium and strontium from waste tanks.

The fuel fabrication facilities that were located in the 300 Area and operated during the timeframe of TLD use were the 333, the 303, and the 306 buildings (Table C.4). Fuel fabrication activities in the 313 and 314 buildings essentially predated the surveillance TLD program and they ceased operation with the shutdown of single-pass reactors at Hanford in 1971. Surveillance TLDs were not deployed in areas where they would record external radiation from these fuel fabrication activities. Fuel fabrication created waste that was transferred to waste management disposal sites located north of the 300 Area on the Hanford Site.

Table C.4. Fuel Fabrication Facilities Years of Operation

Fuel Fabrication				
313 Metal Fuels Fabrication Building	314 Metal Extrusion Building	333 Fuel Cladding Building	303 Billet Storage Facilities	306 Fuel Element Pilot Plant
1944–1971	1944–1971	1961–1988	1944–Present	1957–1984

C.3 Plutonium Finishing Facilities

The plutonium finishing facilities that operated during the timeframe of TLD use were the 232-Z Incinerator Facility, 234-5Z Remote Mechanical A Line (RMA), 234-5Z Remote Mechanical C Line (RMC), 234-5Z Storage Vault, 236-Z Plutonium Reclamation Facility, and 242-Z Waste Treatment Facility (Table C.5). Gerber (2003) provides a detailed discussion of plutonium finishing and facilities. These facilities were located in the 200-West Area and were not covered by the Environmental Surveillance TLD program. They produced some wastes that were transferred to waste disposal sites within the 200-West Area perimeter fence. It is unlikely that wastes resulting from plutonium finishing would have been measured by the Environmental Surveillance TLD Program because no TLDs were placed inside the perimeter fence and they are not capable of measuring alpha radiation as deployed.

In January 1962, the 232-Z incinerator began processing miscellaneous solid wastes to recover small quantities of plutonium. The process involved incineration of combustible materials, leaching noncombustible materials in nitric acid, and wet leaching of ash. The recovered plutonium was transferred to the Recovery of Uranium and Plutonium by Extraction facility (RECUPLEX) and later the Plutonium Reclamation Facility. In 1973, the 232-Z incinerator was shut down.

The 236-Z Plutonium Reclamation Facility (PRF) was placed into operation in May 1964 to recover plutonium from liquid waste generated in the plutonium finishing plant operations.

Table C.5. Plutonium Finishing Facilities Years of Operation

Facility/Process								
231-Z	232-Z	2345Z RG	2345Z RMA	2345Z RMC	2345Z RECUPLEX	2345Z Storage Vault	236-Z	242-Z
1/1945–1989[a]	1/1962–1973	7/1949–1957	3/1952–1984[b]	10/1960–1989[c]	7/1955–1/1962	1949–Present	5/1964–4/1976[d]	1963–1976[e]

(a) In 1956, the mission changed to plutonium metallurgy development; in 19UNK ^{233}U metallurgy studies were undertaken.
(b) In 1964, the line shut down; in 1967, a glovebox was reactivated; in 1968, Tasks I-III were cleaned out and reactivated; in 1984, it was decided to keep the RMA on standby.
(c) In 1962, 10-inch-thick water-filled shielding tanks were added to substantially reduce operator exposure to neutrons. Several safety improvements were made in 1963 and 1964. Fabrication of pits was removed from the line in 1966 and it was shut down in 1976 as a result of explosion in 242-Z. The RMC line restarted in 1985, then shut down in 1989.
(d) In December 1975, it was shut down for upgrades, then restarted in 1976, and shut down in April 1976 as a result of the explosion in 242-Z.
(e) In 1969, the process changed from a batch to a continuous process; in April 1976, it was shut down because of strike, then restarted in August 1976, and finally shut down in August 1976 as a result of an explosion in the americium recovery area.

The 242-Z Waste Treatment Facility began operation in 1963 to recover plutonium from aqueous waste streams from the Plutonium Finishing Plant. An americium-241 recovery process was installed in a glovebox in the 242-Z facility and began operation in May 1965. The recovery process was converted from a batch to a continuous process in 1969. In April 1976, the 242-Z facility was shut down as a result of a strike. In August 1976 during restart of the americium recovery process, an explosion occurred in a

cation ion-exchange column containing approximately 100 grams of americium-241. This resulted in substantial americium exposure to an onsite worker. As a result, the 242-Z facility was permanently closed. Doors into the operating area were welded shut and the facility is currently waiting decontamination and decommissioning efforts.

C.4 Research and Development Facilities

Research and development (R&D) facilities (excluding those discussed previously as part of reactor operations and fuel development (FFTF) that were operational during the period of TLD use at Hanford included the 108-F Biology Laboratory, in which radiation effects studies on plants, animals, and fish were performed in support of Hanford plant operations (Table C.6). Most R&D involving fuel rod composition and production was identified earlier. The 300 Area in general was an R&D area, and at times TLDs were deployed to monitor the 300 Area and waste disposal areas immediately to the north, and the 400 Area. Up to 1977, a biological research facility was maintained at the 100-F Area (108-F) that housed research animals for a number of experiments involving radiological exposure and effects. This research was winding down and most staff transferred to the 300 Area in 1971. The facility was vacated and closed in 1977. Environmental surveillance TLDs were deployed near and around the 300 and 400 Areas, but no specific TLDs were deployed at 100-F because the reactor had been shutdown in 1965.

Table C.6. 300 Area Research and Development Facilities Years of Operation

Facility/Process							
308	318	320	321	324	325	326	327
1960–1990[a]	1983–Present[b]	1966–Present	1944–1988[c]	1966–Present	1953–Present[d]	1953–Present	1953–1987
329	331	3706	3730	3732	3741	3745	
1952–Present	1972–Present	1945–late 1960s[e]	1949–1981	1949–1970	1944–1956	1944–1983[f]	

(a) In the mid-1960s, PRTR fuel work was terminated; Np-Al alloy fuel elements were produced in late 1960s; the high bay area was added in 1971; from 1977–1991, FFTF fuel elements were produced; the 308A Annex was added in 1979; and the Triga reactor was installed in the late 1970s.

(b) The HTLTR reactor commenced operation in the 318 Building in 1967 and was shut down in 19UNK, then removed in the early 1980s. The calibration facility commenced operation in 1983; major additions were added in 1986, 1987, and 1989.

(c) The 321 separation building started in 1944. In late 1944, work involved small amounts of irradiated materials to conduct separations experiments and to study decontamination factors; in 1949, a cold test of REDOX process was performed; a cold test of the PUREX process was conducted in 1953.

(d) The 325-A hot cell wing was added in 1959; Pm-147 heat sources were manufactured in 1966; Po-210 work started in 6/1972 and ended in 1970. Presently supports the demonstration of the Waste Vitrification Process for commercial wastes.

(e) Most of the radiation laboratories were removed in 1954. Work with radioactive materials was discontinued in the late 1960s, and the building was converted to offices in the 1970s and was still in use in the early 1990s.

(f) The 3745-B Annex that housed a 4-MV positive ion accelerator started operation in 1955. The 3745-A annex that housed a 2-MV negative ion accelerator started operation in 1950. The calibrations operations were transferred to the 318 Building in 1983; the building is being used as office space.

Many R&D facilities also operated in the 300 Area at Hanford. These facilities are often identified by a building number that supported a number of activities (Table C.6). Additional information about R&D activities and associated facilities can be found in the report by Noonan and Stapp (2003).

C.5 References

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