PNNL-10354
Rev. 2

Radiation and Health Technology Laboratory Capabilities

July 2005

Pacific Northwest
National Laboratory
Operated by Battelle for the
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PACIFIC NORTHWEST NATIONAL LABORATORY
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On the Cover

A calibration technician in the Radiological Calibration and Standards Laboratory performing a bench-top calibration of an alpha-sensitive continuous air monitor. The laboratory calibrates more than 16,000 radiation detection instruments a year.

Torso calibration phantoms are used at the In Vivo Radio-assay and Research Facility to calibrate lung-counting systems.

The shielded enclosure around the k-fluorescence x-ray machine provides a "clean" spectrum for performing nearly mono-energetic photon energy response testing of instruments and dosimeters. The researcher is setting up a horizontal angular dependence evaluation of finger ring dosimeters.

This document is intended to serve as a reference guide for PNNL staff and clients who desire technical information about the broad capabilities of the Radiation and Health Technology Laboratories. The document has been expanded and revised several times to add additional information as requested by its users. We welcome comments and suggestions for future revisions. Please contact Michelle Johnson at 509-376-4014 or the calibration laboratory via e-mail at calibration@pnl.gov.

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Radiation and Health Technology Laboratory Capabilities

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Summary

The Radiation and Health Technology (R&HT) technical group at Pacific Northwest National Laboratory (PNNL) provides a broad mix of calibration and testing services within a single organization. Its staff of more than 50 individuals includes several nationally recognized leaders in the fields of dosimetry, performance testing, and radiological calibrations. The laboratory provides a unique mix of radiological and environmental testing and characterization facilities that give clients access to a broader variety of test capabilities than is typically available within a single laboratory. The organization performs calibrations on radiological instruments, sources, and passive dosimetry; maintains the reference standards necessary to trace the Hanford Site programs and other research- and quality-related programs to national standards; performs environmental effects testing on equipment and materials; performs non-destructive assay for special nuclear material; and performs in vivo assay of radioactive materials.

This document describes R&HT's facilities and capabilities. It is intended to be used as a reference guide by PNNL staff and clients who require information on the wide range of radiological, environmental, and evaluation laboratory capabilities provided by the R&HT.

The specialized facilities developed to support calibrations, dosimetry, in vivo bioassay, and instrument performance evaluations include the following:

- A low-scatter room that provides neutron (heavy water [$D_2$0-] moderated and unmoderated ^{252}Cf) and gamma (^{60}Co and ^{137}Cs) irradiations in a free-space geometry.

- A source well room equipped with four calibration source wells (three gamma and one neutron) designed to expedite routine instrument calibrations.

- A photon laboratory that meets the specifications of the National Institute of Standards and Technology and International Standards Organization for bremsstrahlung and K-fluorescent x-ray spectra, and gamma reference fields using an open (2π) ^{241}Am source and a collimated beam ^{137}Cs irradiator.

- A high-exposure facility capable of delivering a large-volume, uniform gamma radiation field (up to 5×10^4 R/h) for calibrations or evaluating the effects of radiological dose on materials.

- A beta-particle laboratory that maintains ^{85}Kr, ^{204}Tl, ^{147}Pm, and ^{90}Sr/^{90}Y as international secondary standard sources for instrument and dosimetry characterization.

- An instrument calibration laboratory with the flexibility required to calibrate a wide range of portable and semi-portable measurement and test equipment, radiological instrumentation, and radioactive sources.
- An environmental effects laboratory for evaluating the response of materials and equipment to environmental influences, including evaluating the performance of health physics instruments against American National Standards Institute and other performance standards.
- The U.S. Department of Energy-accredited thermoluminescent dosimetry laboratories that directly support the Hanford Site personnel, environmental, and nuclear accident dosimetry programs.
- A medical seed laboratory for performing American Association of Physicists in Medicine TG-43 dosimetric evaluations on very small brachytherapy seeds used for cancer therapy.
- An in vivo bioassay facility equipped with six counting systems for measuring low levels of radioactive materials in the human body.
- A non-destructive analysis laboratory that is capable of performing measurements on a variety of waste containers, including 55-gallon drums, assorted boxes and casks, and measurements of onsite/offsite radiological sources (e.g., hold-up mesaurements in facilities, emergency monitoring in the field).

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Acronyms

AAPM	American Association of Physicists in Medicine
AC	alternate current
ADCL	accredited dosimetry calibration laboratories
ANSI	American National Standards Institute
BOMAB	bottle manikin absorption (phantom)
CAM	Continuous Air Monitor (Facility)
CFR	Code of Federal Regulations
CLIR	Calibration Laboratory for Ionizing Radiation
DC	direct current
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
DSA	digital signal analyzer
EIC	extrapolation ionization chamber
FNAD	fixed nuclear accident dosimeter
FWHM	full width, half maximum
HTLTR	High-Temperature Lattice Test Reactor
HPGe	high-purity germanium (detector)
IAEA	International Atomic Energy Agency
ISO	International Standards Organization
IS&T	Instrumentation Services and Technology
IVMP	In Vivo Monitoring Program
IVRRF	In Vivo Radioassay and Research Facility
LSR	low-scatter room
MCA	multichannel analyzer
MDA	minimum detectable activities
M&TE	measuring and test equipment
NDA	non-destructive analysis
NIST	National Institute of Standards and Technology
NVLAP	National Voluntary Laboratory Accreditation Program
PNAD	personal nuclear accident dosimeter
PNNL	Pacific Northwest National Laboratory
PTB	Physikalisch-Technische Bundesanstalt
RESL	Radiological Environmental Sciences Laboratory
RF	radio frequency
RH	relative humidity
R&HT	Radiation and Health Technology
TED	track-etch dosimeter
TLD	thermoluminescent dosimeter

1.0 Introduction

Radiation and Health Technology (R&HT), a part of Pacific Northwest National Laboratory (PNNL),[a] performs a variety of services, including calibrations, dosimetry processing, non-destructive analysis (NDA), and environmental effects testing. The organization manages several major facilities, including the Radiation Standards and Calibration Laboratory and the In Vivo Radioassay and Research Facility (IVRRF). The laboratories support:

- U.S. Department of Energy (DOE) programs at the Hanford Site in south-central Washington State and at other DOE and commercial nuclear sites.
- Programs sponsored by DOE Headquarters and other federal agencies.
- Research and characterization programs sponsored through the commercial sector.

R&HT occupies several facilities, including the 318 Building in the 300 Area of the Hanford Site and the 747A Building, located in downtown Richland, Washington.

This document describes R&HT's facilities and capabilities. It is intended to be used as a reference guide by PNNL staff and clients who require information on the wide range of radiological, environmental, and evaluation laboratory capabilities provided by the R&HT.

(a) Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC05-76RLO 1830.

2.0 Radiation Standards and Calibration Laboratory Capabilities

The laboratory capabilities, and staff who manage these capabilities, are located mostly in the Hanford Site's 318 Building (Figure 2.1). The building was originally a test reactor facility, which was selected for the Radiation Standards and Calibration Laboratory because it contains a large, shielded reactor containment room that was converted to the low-scatter irradiation facility (Figure 2.2). The 318 Building contains an unusually robust and varied range of technical capabilities, from routine radiological calibration facilities to state-of-the-art photon energy response testing facilities.

***Figure 2.1**. Radiological Standards and Calibration Laboratory. Original reactor and associated office building (foreground) and; Phase I and Phase III, south-wing building additions (to left).*

There are five major exposure rooms (Figure 2.3) and several laboratories used for exposure work preparation, instrument calibrations, instrument performance evaluations, instrument maintenance, instrument design and fabrication work, and thermoluminescent and radiochromic dosimetry. The major exposure facilities are a low-scatter room (LSR) used for neutron and photon exposures, a source well room used for high-volume radiological calibration work, an x-ray facility used for energy response studies, a High-Exposure Facility used for high-rate photon calibration work and radiation hardness tests, a beta standards laboratory used for beta energy response studies and beta reference calibrations, and measuring and test equipment (M&TE) calibration laboratories. Many of the ionizing radiation facilities and processes in the 318 Building are part of the National Voluntary Laboratory Accreditation Program (NVLAP)-accredited ionizing radiation laboratory (NVLAP Lab Code 105020-0) maintained by the Calibration Research and Accreditation Group. This group utilizes these facilities to provide transfer standard calibrations, particularly for neutron and gamma fields and for calibration and irradiation facilities across the United States. They conduct performance testing for all NVLAP-accredited dosimetry processors and support the Department of Energy Laboratory Accreditation Program (DOELAP) for DOE.

***Figure 2.2.** The High-Temperature Lattice Test Reactor (HTLTR) was part of the fuels diversification research being carried out at the Hanford Site to facilitate "peaceful atom" projects. The HTLTR conducted research and data collection to gain more knowledge about high-temperature reactor physics. The test reactor operated from 1968 to 1972.*

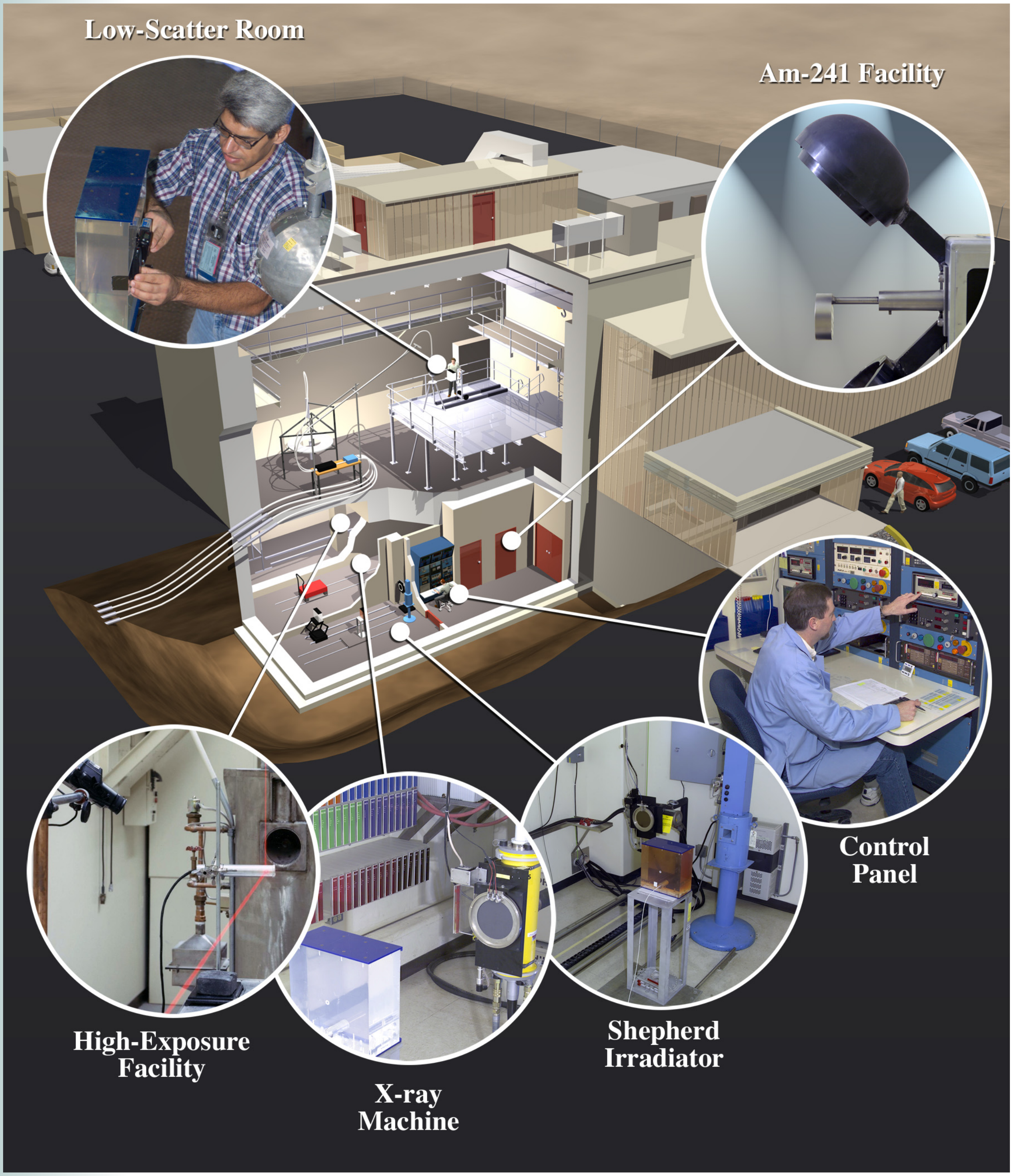

Figure 2.3 *318 Building Ionizing Radiation Laboratories. The 318 building contains a wide variety of ionizing radiation laboratories and radiation generating devices, many of which are housed in the former reactor containment illustrated here.*

2.1 Irradiation Laboratories

The irradiation laboratories are located in the 318 Building, the upper containment area, a concrete room of dimensions 10 x 9 x 15 meters, was converted into a low-scatter facility, and its lower containment area was partitioned into x-ray and high-exposure facilities. On the ground floor, outside the low-scatter facility are the beta standards laboratory and the source well room.

Figure 2.4. The Laboratory's LSR. This facility is suitable for neutron and photon irradiation of devices that may be sensitive to scattered radiation. The facility is equipped with two irradiation stations. The position shown at lower left is predominantly used for photon irradiations of personnel dosimeters using either ^{137}Cs or ^{60}Co sources. The position on the platform is located near the geometric center of the room and is used for neutron irradiations.

Low-Scatter Room

The LSR provides for uncollimated neutron and gamma reference fields for both active detector response characterization and passive personnel dosimetry systems, following current DOE, International Standards Organization (ISO), and American National Standards Institute (ANSI) standards. Irradiation quality control is aided by installed off-axis monitors.

The LSR (shown in Figure 2.4) is a large irradiation area with a relatively low and easily quantified albedo for the neutron calibration station housed within it. The room has concrete walls and measures approximately 10 x 9 x 15 meters. The neutron source irradiation station is mounted on a raised aluminum platform, located approximately at the geometrical center of the room (Figure 2.5). Another irradiation station is located at the floor level (Figure 2.6). A pneumatically driven "rabbit" system is used to move sources from their storage locations to any of the irradiation stations. The exposure control console allows the operator to select the source and station along with the irradiation duration, provides an indication of the source position (either in storage or at a station), and will automatically return the source to storage and shut down the system in case of a malfunction in the safety system.

The functional capabilities of each of the irradiation stations within the LSR are described below for the sources available within the facility. (Tables 2.1 and 2.5 provide additional information on the source geometries and available exposure rates.)

- The elevated neutron station is used for D_2O-moderated ^{252}Cf irradiations, as specified by various DOE, American, and International Standards (DOE 1986; ANSI 1993, 1989a, b). Bare ^{252}Cf irradiations specified in some of these standards are also carried out at this station by removing the D_2O moderator sphere.

Figure 2.5. The LSR Tower Irradiation Position. This position allows for irradiation using photon or neutron sources. Neutron irradiations may be performed with either a bare source configuration or using a moderator assembly, such as the cadmium-covered D_2O sphere shown here. While most dosimeters are irradiated at a distance of 50 cm from the source, instrument calibrations are accomodated by a flexible positioning system, which has a range extending to about 3 meters. Based on room return evaluations, appropriate corrections are made to ensure that instrument calibrations are normalized to free-field conditions.

***Figure 2.6**. Floor-Level Station in the LSR. This station is used for photon irradiations. Dosimeters may be placed at distances from 50 to 100 cm from the source position. The supporting structure is composed of low atomic number materials and is rigid enough to prevent warping. With available positioning jigs, dosimeters may be placed at equal distances in circumference around the source position. An air-ionization chamber provides irradiation quality control.*

- The floor-level station is used for bare ^{252}Cf, ^{60}Co, and ^{137}Cs irradiations (Figure 2.6). The station has a ring-shaped table constructed of low-density foam to minimize scatter. This table supports pencil and thermoluminescent dosimeters at distances of 50 and 100 cm from the source. The ring design enables the simultaneous irradiation of many artifacts to a single source.

- Additional sealed sources may be used within the facility for special calibration or characterization needs. The sources currently used include ^{137}Cs (about 10 mCi), various beta sources, and an ^{241}AmBe (3-Ci) neutron source.

Neutron traceability to national standards is established through the calibration of sources at the National Institute of Standards and Technology (NIST), in terms of total neutron emission rate, using the manganous sulfate bath method. Gamma sources are calibrated using NIST-traceable, reference-class, air-equivalent ionization chambers.

Table 2.1. Neutron Reference Fields

Geometry	Isotope (Source No.)	Nominal Rate/Range[a] (mrem/h)	Fluence Average Energy (MeV)
Open (4π)	^{252}Cf Bare (318-016)	0.079 to 2.9	2.13[b]
	^{252}Cf Bare (318-038)	0.98 to 36	
	^{252}Cf Bare (318-167)	5.8 to 210	
	^{252}Cf Bare (318-404)	300 to 11000	
	^{252}Cf Moderated (318-016)	0.022 to 0.79	0.55[b]
	^{252}Cf Moderated (318-038)	0.24 to 8.8	
	^{252}Cf Moderated (318-167)	1.5 to 54	
	^{252}Cf Moderated (318-404)	73 to 2600	
	AmBe (318-286 & 318-287)	25 to 1	4.16[c]
	AmBe (318-289)	100 to 3	
Well	^{252}Cf Bare (318-356)	600[d] to 1	2.13[b]

(a) Rates current as of 3/2005 and calculated in terms of ICRP-21 fluence-to-dose equivalent relationship
(b) Value obtained from ANSI Standard HPS N13.11-2001, *Personnel Dosimetry Performance - Criteria for Testing*.
(c) IAEA Technical Report Series 188, 1979
(d) Dependent upon instrument response to scatter spectrum

X-Ray Facilities

The PNNL x-ray facility offers quality-controlled irradiation application for both photon detector response characterization and personnel dosimetry systems, following current DOE, ISO, and ANSI standards. Delivered air-kerma is accurately determined via a calibrated transmission chamber and verified using an off-axis quality-control monitor.

The x-ray laboratory consists of a shielded control panel and a 4.7 x 12.6 x 4.0 meters irradiation room. Two identical Philips Model-324 x-ray machines (Figure 2.7) are currently used to support instrument calibration and personnel dosimetry activities. One machine produces bremsstrahlung photon spectra (using NIST and ISO techniques), while the second is configured to facilitate production of K-fluorescence technique (i.e., narrow) secondary photon spectra (e.g., F-Mo, F-W) within a shielded enclosure (Figure 2.8). Tables 2.2 through 2.4 provide complete lists of available techniques and their characteristics. Both x-ray-generating systems use laser-alignment systems to aid in positioning the instruments or dosimeters.

Traceability of calibrations to NIST for bremsstrahlung x-ray techniques is via a library of reference-class, air-equivalent ionization chambers calibrated directly at NIST for each specific x-ray technique. Measurement quality assurance interactions (i.e., proficiency testing) with NIST, using reference-class intercomparison standards, demonstrate ongoing measurement traceability. Instruments using fluorescence x-ray techniques are calibrated using reference-class, air-equivalent ionization chambers that have been calibrated at NIST using bremsstrahlung x-ray methods with energies in the vicinity of each characteristic x-ray. Similar to the methodology employed for ^{241}Am, the specific air-equivalent ionization chamber correction coefficient for each K-fluorescence technique is interpolated from these calibrations.

Figure 2.8. *Philips Model 324 X-Ray Machine. K-fluorescence beams are extracted at a 90° angle from the incident x-ray beam direction. A special shielded enclosure is used by PNNL to maintain "clean" spectra.*

Figure 2.7. *Two Philips Model 324 X-Ray Units. Both are available for performing various dosimeter irradiations and instrument reponse evaluations. The unit on the left is configured to produce most NIST and several ISO techniques. The unit on the right is used for generating ISO/K-fluorescence techniques, which are useful for specific photon energy response evaluations from energies as low as 8.6 keV to 59.3 keV.*

Table 2.2. Available "Broad Spectra" Bremsstrahlung X-Ray Reference Fields

Code	Avg. Energy[(a,b)]	Resolution[(c)]	Half Value Layer (mm)[(b)]		Homogeneity Coefficient[(b)]		Nominal Exposure Rate (R/h)[(d)]	
			Al	Cu	Al	Cu	Minimum	Maximum
ISO High Air Kerma Rate Series								
HK30	19.7	66	0.38	0.013	63	72	3	500
HK60	37.3	70	2.42	0.079	74	72	2	300
HK100	57.4	75	6.56	0.30	81	64	2	400
HK200	102	85	14.7	1.70	95	71	4	600
HK250	122	87	16.6	2.47	96	75	6	800
HK280	146	54	18.6	3.37	98	84	6	600
HK300	147	82	18.7	3.40	97	82	7	800
NIST Light Filtration Series								
L40	23	83	0.5	—	59	—	4	740
L50	28	82	0.76	—	60	—	4	840
L80	40	88	1.83	—	57	—	5	1000
L100	48	96	2.77	—	57	—	6	1200
NIST Moderate Filtration Series								
M20	14	58	0.15	—	69	—	3	600
M30	20	65	0.36	—	65	—	3	500
M40	25	72	0.73	—	69	—	3	500
M50	29	79	1.02	—	66	—	3	700
M60	35	80	1.68	—	66	—	3	600
M100	53	79	5.02	—	73	—	3	600
M150	73	81	10.2	0.67	87	62	4	800
M200	100	87	14.9	1.69	95	69	4	650
M250	139	76	18.5	3.2	98	86	4	500
M300	206	56	22	5.3	100	97	2	175
NIST Special Filtration Series								
S75	40	88	1.86	—	63	—	4	880
S60	38	71	2.77	—	72	—	1	230
ISO Wide Series								
WS60	45	48	—	0.18	—	86	0.2	40
WS80	57	55	—	0.35	—	80	0.3	68
WS110	79	51	—	0.96	—	86	0.2	50
WS150	104	56	—	1.86	—	89	0.6	100
WS200	137	57	—	3.08	—	93	1	160
WS250	173	56	—	4.22	—	96	1	160
WS300	208	57	—	5.20	—	97	1	170

(a) Nominal
(b) Value obtained from ANSI Standard HPS N13.11-2001, *Personnel Dosimetry Performance - Criteria for Testing* and/or ISO4037-1: 1996(E).
(c) Calculated value using FWHM and Average Energy (Ç) as reported in Tables 2a and 2b of ANSI Standard HPS N13.11-2001, *Personnel Dosimetry Performance - Criteria for Testing*. [(FWHM/Ç)*100]
(d) Minimum and maximum exposure rates based on usable range of the x-ray machine output.

Table 2.3a. Available "Narrow Spectra" Bremsstrahlung X-Ray Reference Fields

Code	Avg. Energy[(a,b)]	Resolution[(c)]	Half Value Layer (mm)[(b)]		Homogeneity Coefficient[(b)]		Nominal Exposure Rate (R/h)[(d)]	
			Al	Cu	Al	Cu	Minimum	Maximum
NIST Heavy Filtration Series								
H30	24	31	1.23	—	93	—	0.06	12
H40	33	28	2.9	—	90	—	0.02	5
H50	39	36	4.2	0.142	92	90	0.07	13
H60	47	36	6.0	0.24	94	89	0.07	13
H100	83	28	13.5	1.14	100	94	0.02	3
H150	118	37	17.0	2.5	100	95	1	21
H200	162	32	19.8	4.1	100	99	1	14
H250	204	30	22	5.2	100	98	0.9	10
H300	251	27	23	6.2	99	98	0.6	6
ISO Low Air Kerma Rate Series								
LK30	26	21	1.46	—	99	—	0.002	0.4
LK35	30	21	2.20	—	99	—	0.008	2
LK55	48	21	—	0.25	—	99	0.005	1
LK70	60	22	—	0.49	—	99	0.005	1
LK100	87	22	—	1.24	—	99	0.005	1
LK125	109	21	—	2.04	—	99	0.005	1
LK170	149	18	—	3.47	—	99	0.05	0.8
LK210	185	18	—	4.54	—	100	0.05	0.7
LK240	211	18	—	5.26	—	100	0.05	0.6
ISO Narrow Series								
NS20	16	34	0.32	—	86	—	0.2	40
NS25	20	33	0.66	—	90	—	0.1	30
NS30	24	32	1.15	—	88	—	0.07	15
NS40	33	30	—	0.084	—	92	0.04	8
NS60	48	36	—	0.24	—	92	0.06	14
NS80	65	32	—	0.58	—	94	0.03	7
NS100	83	28	—	1.11	—	95	0.02	4
NS120	100	27	—	1.71	—	97	0.02	4
NS150	118	37	—	2.36	—	96	1	28
NS200	164	30	—	3.99	—	99	0.6	8
NS250	208	28	—	5.19	—	99	0.6	7
NS300	250	27	—	6.12	—	100	0.6	6

(a) Nominal
(b) Value obtained from ANSI Standard HPS N13.11-2001, *Personnel Dosimetry Performance - Criteria for Testing* and/or ISO 4037:1-1996
(c) Calculated value using FWHM and Average Energy (Ç) as reported in Tables 2a and 2b of ANSI Standard HPS N13.11-2001, Personnel Dosimetry Performance - Criteria for Testing. [(FWHM/Ç)*100]
(d) Minimum and maximum exposure rates based on usable range of the x-ray machine output.

Table 2.3b. Available "Narrow Spectra" K-Fluorescence X-Ray Reference Fields

Code[(a)]	Theoretical Peak Energy (keV)[(b)]	Production Method			Nominal Exposure Rate (R/h)[(c)]	
		Radiator/ Attenuator	Filter	kVp	Minimum	Maximum
ISO Fluorescence Series						
F-Zn	8.6	Zinc	None	50	0.13	19.8
F-Zr	15.8	Zirconium	$SrCO_3$	80	0.02	3.2
F-Mo	17.5	Molybdenum	Zr	80	0.02	3.4
F-Sn	25.3	Tin	Ag	100	0.02	3.5
F-Cs	31	Cesium	TeO_2	100	0.02	3.2
F-Nd	37.4	Neodymium	Ce	110	0.009	1.4
F-Sm	40.1	Samarium	CeO_2	120	0.01	1.4
F-Er	49.1	Erbium	Gd_2O_3	120	0.005	0.8
$F\text{-}W_c$	59.3	Tungsten	Yb_2O_3	170	0.005	0.8
$F\text{-}W_m$	59.3	Tungsten	Yb	170	0.006	0.9

(a) As identified by ISO 4037-3 (1999). Subscripts on F-W techniques differentiate between filters made of chemical compound (c) and pure metal (m). All techniques use a 1.0-mm aluminum prefilter with the exception of the F-Zn technique, which uses a 5-mm prefilter.
(b) Nominal
(c) Minimum and maximum estimated at 0.1 and 20.0 mA, respectively

^{241}Am Exposure Laboratory

Figure 2.9. ^{241}Am Source. This source provides a 60-keV photon calibration field.

The ^{241}Am exposure capability provides a low-energy (60-keV) gamma reference field per the ISO-4037, which can be used for characterization of both instruments and personnel dosimetry systems (ISO 1996, 1997, 1999). When used to irradiate dosimeters, delivered air-kerma is verified using an off-axis quality-control monitor.

PNNL uses a modified Atlan-Tech irradiator (see Figure 2.9), equipped with an Amersham Model AMC50, 185-GBq (5-Ci), ^{241}Am source. The source is 40 mm in diameter and encapsulated on the front by 0.25 to 0.30 mm of stainless steel. The 2π reference field is calibrated at a distance of 50 cm, providing an air-kerma rate of approximately 1 mGy/h (0.12 R/h). Table 2.5 includes additional information on the source geometries and available exposure rates.

This source is calibrated using a reference-class, vented air-equivalent ionization chamber, which has been calibrated at NIST for several photon energies, including ^{137}Cs, ^{60}Co, and a variety of x-ray fields. However, because NIST does not maintain this specific reference field, the chamber is not calibrated specifically for ^{241}Am. The specific calibration factor applied to the air-equivalent ionization chamber for this calibration has been obtained by interpolation of two bremsstrahlung x-ray techniques, having average energies that bracket the primary photon energy of the ^{241}Am source. These x-ray techniques are M100 (E_{avg} = 53 keV) and M150 (E_{avg} = 73 keV). In 1997, a three-way measurement intercomparison of ^{241}Am source reference fields at PNNL, the Radiological Environmental Sciences Laboratory (RESL), and the National Physical Laboratory in the United Kingdom was orchestrated by RESL. This intercomparison demonstrated consistency of all three fields within 2%.

Table 2.4. Available X-Ray Reference Fields (sorted) by Average Energy

NOTE: See NIST Special Publication 250-58, *Calibration of X-Ray and Gamma-Ray Measuring Instrument*, Section 4.2 for recommendations on beam code selection and possible discontinuities.

Broad Spectra		Narrow Spectra	
Code	**Average Energy**	**Code**	**Average Energy**
M20	14	F-Zn	8.6
HK30	19.7	F-Zr	15.8
M30	20	NS20	16
L40	23	F-Mo	17.5
M40	25	NS25	20
L50	28	H30	24
M50	29	NS30	24
M60	35	F-Sn	25.3
HK60	37.3	LK30	26
S60	38	LK35	30
L80	40	F-Cs	31
S75	40	H40	33
WS60	45	NS40	33
L100	48	F-Nd	37.4
M100	53	H50	39
WS80	57	F-Sm	40.1
HK100	57.4	H60	47
M150	73	LK55	48
WS110	79	NS60	48
M200	100	F-Er	49.1
HK200	102	$F\text{-}W_c$	59.3
WS150	104	$F\text{-}W_m$	59.3
HK250	122	LK70	60
WS200	137	NS80	65
M250	139	H100	83
HK280	146	NS100	83
HK300	147	LK100	87
WS250	173	NS120	100
M300	206	LK125	109
WS300	208	H150	118
		NS150	118
		LK170	149
		H200	162
		NS200	164
		LK210	185
		H250	204
		NS250	208
		LK240	211
		NS300	250
		H300	251

Table 2.5. Gamma Reference Fields

Geometry	Isotope	Nominal Rate(s)(a) (R/h)	Average Energy (MeV)(b)
Beam	^{60}Co	1.1 to 350(c) 12 to 4000(d)	1.250
	^{60}Co	0.12 to 38(c) 1.4 to 400(d)	
	^{60}Co	5.5 to 1800(c) 63 to 20000(d)	
	^{137}Cs	0.0006 to 0.22(c) 0.06 to 21(d)	0.662
	^{137}Cs	0.007 to 2.1(c) 0.64 to 200(d)	
	^{137}Cs	2.0 18	
Open (2π)	^{241}Am	0.118	0.060
Open (4π)	^{60}Co	0.27 1.0	1.250
	^{137}Cs	0.30 1.1	0.662
	^{137}Cs	6.0 1.6	
	^{226}Ra	19.12	Multiple Peaks
Well	^{137}Cs	0.8 to 6.0(c) 1.0 to 100(d)	0.662
	^{137}Cs	3.7 to 800(c) 60 to 14000(d)	

(a) Rates current as of 3/2005
(b) Value obtained from ANSI Standard HPS N13.11-2001, *Personnel Dosimetry Performance - Criteria for Testing*
(c) Attenuated (Pb)
(d) Unattenuated

Figure 2.10. The J.L. Shepherd Model 81, 100-Ci ^{137}Cs Irradiator (right). This equipment is available for performing dosimeter irradiations or instrument calibrations. A Pantak Model HF320C x-ray machine (left and behind the phantom) is available for generating NIST and ISO beam techniques. The associated x-ray irradiation platform is capable of rotating and can be used to perform static and dynamic angular response studies.

Shepherd Irradiator

This high-energy ^{137}Cs gamma reference field is maintained for dosimetry and instrument irradiation, calibration, and testing. The field is established in accordance with ISO-4037 to deliver air-kerma under conditions of electronic equilibrium and can be used for characterization of both instruments and personnel dosimetry systems. When used to irradiate dosimeters, delivered air-kerma is verified using an off-axis quality-control monitor.

The reference field is provided using a J.L. Shepherd, Model 81 irradiator (see Figure 2.10). This irradiator employs a 3.7-TBq (100-Ci) ^{137}Cs source and emits a 30° collimated photon beam. The reference field is calibrated at two distances on the beam axis, 1 and 3 meters, with air-kerma rates of approximately 160 mGy/h (18.3 R/h) and 17 mGy/h (2.0 R/h), respectively. Table 2.5 includes additional information on the source geometries and available exposure rates.

Traceability of the reference field is via one or more reference-class, air-equivalent ionization chambers calibrated directly at NIST. Measurement quality assurance interactions (i.e., proficiency testing) with NIST, using reference-class intercomparison standards, demonstrate ongoing measurement traceability.

High-Exposure Facility

The High-Exposure Facility (see Figure 2.11) is capable of delivering a uniform high-energy gamma radiation field of approximately 5.0 x 10^{-7} mGy/h (0.0006 R/h) to 17.6 mGy/h (2 x 10^{4} R/h) for standard calibration of testing or radiation-measuring instruments. Additionally, this facility provides ^{60}Co irradiation capability for the irradiation of personal dosimetry devices. Table 2.5 includes the current radiation sources and exposure capabilities of the facility. When used to irradiate dosimeters, delivered air-kerma is verified using an off-axis quality-control monitor.

This facility, which measures 15.2 x 3.7 x 3.7 meters, has multiple ^{137}Cs and ^{60}Co encapsulated sources that are pneumatically raised into exposure position from a shielded carousel located below floor-level. In the exposure position, the source capsule is shielded by a 2.5-ton lead-shielded exposure column that establishes the exposure (beam) geometry. A 30° conical opening (15° cone angle) presents a horizontal radiation field about 1.5 meters above the floor. Instrument detectors or dosimeters are placed on a remotely operated, lightweight aluminum trolley cart in front of the cone opening.

For instruments with remote readout capability, the detector can be positioned on the trolley cart and connected to remote readout cabling, which runs from the trolley cart to the remote operator console. Operations may then be conducted at the console located outside the concrete-shielded exposure room. For instruments that cannot be operated remotely, a closed-circuit TV camera is used to monitor instrument responses from the remote operator console (Figure 2.12). From the console, the sources can be selected and raised into exposure position. The trolley cart can also be positioned and repositioned to any location along the 6-meter track. The combination of long trolley track and the variety of sources allows a wide range of exposure rates to be generated within the facility.

Traceability of reference fields is via one or more reference-class, air-equivalent ionization chambers calibrated directly at NIST. Measurement quality assurance interactions such as proficiency testing with NIST, using reference-class intercomparison standards, demonstrate ongoing measurement traceability.

Figure 2.11*. The High-Exposure Facility. This facility is used for high-level ^{137}Cs and ^{60}Co photon irradiations and calibrations. The irradiation unit pneumatically lifts the source into the irradiation position. This facility is equipped with positioning lasers that aid initial setup of dosimeters or instruments within the central beam axis at a distance of 1 meter. Cameras are positioned to remotely monitor instrument readings during irradiation.*

Beta Standards Laboratory

The 318 Building contains two commercial beta secondary standard systems that use "point" sources. These systems are used to perform instrument response characterizations and irradiation of personal dosimeters in accordance with the guidance of current DOE, ISO, and ANSI standards. When used to irradiate dosimeters, delivered dose is verified using an off-axis quality-control monitor. In addition to the point source irradiation systems, a depleted uranium slab source is available to provide irradiation of dosimeters in accordance with ANSI N13.32 and DOE/EH-0027 (DOE 1986).

The beta irradiators (shown in Figure 2.13) consist of a source jig, an operator console, and various beta sources including $^{90}Sr/^{90}Y$, ^{85}Kr, ^{147}Pm, and ^{204}Tl. Dosimeters mounted on phantoms and instruments may be irradiated at specific distances based on the characterization of the source. Reference field uniformity is enhanced by beam-flattening filters, where applicable or necessary. A list of available sources is provided in Table 2.6.

Figure 2.12*. The High-Exposure Facility Control Room. The facility is remotely controlled from the panel, which also houses the monitors for remote cameras within the radiation area and allows for remote positioning of instruments.*

Figure 2.13. *A Buchler-Amersham Irradiation Jig and Point Source Inventory are the Basis for PNNL's Beta Irradiations. The system has been configured to be computer controlled for automated exposures and to monitor critical quality control information such as temperature, pressure, humidity, and the signal from an ionization chamber mounted in the phantom used for dosimeter irradiations.*

Traceability of beta reference fields is initially based on those specific sources calibrated by Physikalisch-Technische Bundesanstalt (PTB) or NIST. Those sources that do not have direct traceability have been calibrated in-house using a commercial extrapolation ionization chamber (EIC). The EIC is considered to be an absolute standard; however, its use is based on the accurate knowledge of its physical characteristics. These characteristics are confirmed via sources calibrated by PTB or NIST. Occasional measurement quality assurance interaction (i.e., proficiency testing) with NIST demonstrates ongoing measurement traceability.

Table 2.6. Beta Source Reference Fields

Geometry	Isotope $_{\text{(Source No.)}}$	Window Materials and Areal Density (mg/cm^2)	Protective Coating Material and Areal Density (mg/cm^2)	Residual Maximum Energy – E_{res} (MeV) (M-Measured, T-Theoretical)	Absorbed Dose Rate[a] (rad/h) [Calibration Distance (cm)]
Point	^{147}Pm $_{(318\text{-}290)}$	n/a	Titanium (2.3)	0.1504 (M)	0.011 (20)
	^{147}Pm $_{(318\text{-}401)}$	Titanium (2.22)	None	0.1504 (T)	0.16 (20)
	^{204}Tl $_{(318\text{-}109)}$	Silver (20)	Gold (5)	$0.53 \le E_{res} \le 0.69$ (T)	0.002 (30)
	^{204}Tl $_{(318\text{-}360)}$	Acrylic (0.2)	Kapton (9)	0.557 (M)	1.0 (35)
	^{85}Kr $_{(318\text{-}402)}$	Titanium (22.5)	None	$0.53 \le E_{res} \le 0.76$ (T)	11.5 (30)
	^{90}Sr/^{90}Y $_{(318\text{-}013)}$	Silver (50)	Stainless Steel (~75)	$1.80 \le E_{res} \le 2.274$ (T)	0.42 (30)
	^{90}Sr/^{90}Y $_{(318\text{-}102)}$	Titanium (100)	Aluminum (20)	$1.80 \le E_{res} \le 2.274$ (T)	0.38 (35)
	^{90}Sr/^{90}Y $_{(318\text{-}012)}$	Silver (50)	Stainless Steel (~75)	2.046 (M)	17 (30)
	^{90}Sr/^{90}Y $_{(318\text{-}103)}$	Titanium (100)	None	2.085 (M)	12 (35)
	^{90}Sr/^{90}Y $_{(318\text{-}403)}$	Stainless Steel (80)	None	$1.80 \le E_{res} \le 2.274$ (T)	3.2 (30)
Distributed	^{14}C $_{(318\text{-}032)}$	Not Available	PMMA[b]	Has not been measured for these sources.	2.2 (0.2)
	^{147}Pm $_{(318\text{-}113)}$	Not Available	Kapton (1.5)		0.08 to 0.001 (0.2 to 1.5)
	^{204}Tl $_{(318\text{-}128)}$	Not Available	Kapton (9.5)		0.24 to 0.01 (0.2 to 30)
	^{90}Sr/^{90}Y $_{(318\text{-}129)}$	Not Available	Kapton (23.5)		3.5 to 0.14 (0.2 to 30)
	Depleted Uranium $_{(318\text{-}166)}$	Not Available	Aluminized Mylar (7)		0.204 (0.15)

(a) Nominal at 7 mg/cm^2 as of 3/2005
(b) The source is polymerized with the Polymethylemethacrylate. Sheet thickness in approximately 1 mm with activity uniformly distributed throughout.

2.2 Radiological Calibration Laboratories

The Instrumentation Services and Technology (IS&T) group provides complete calibration and repair services. In addition to supporting the Hanford contractors' radiological programs, customers include DOE, the Department of Homeland Security, utilities, universities, state agencies, the Canadian government, and biotech, research, and industrial firms. The large variety of alpha, beta, photon, and neutron standards, and experience and trained staff, and ISO-17025 (ISO 1990) compliant quality program and procedures, can service many types of radiological health instrument and equipment, including:

- Fixed monitoring equipment, including portals and contamination monitors.
- Portable survey instruments, including exposure and contamination instruments.
- Air sampling and continuous air-monitoring instruments.
- Electronic and quartz fiber dosimeters.
- Bench-top alpha and beta monitors and scalers.
- Environmental monitors.
- M&TE.

Re-certification of alpha and beta source emission rates or activities can also be performed.

The unique capabilities, which many customers rely upon, include calibrations of environmental, high photon exposure rates (>2000 R/h), neutron dose rate, and tritium air monitors.

Instruments and/or sealed sources are delivered to the laboratory's receiving room, where they are logged in (Figure 2.14). Following check-in, an instrument is routed to the repair shop or to either the source well room or an appropriate calibration laboratory, depending on the state of the instrument and its purpose.

Figure 2.14. *Instrument Receiving Room. Radiological instruments are received from clients in the Instrument Receiving Room. After they are logged into the database, instruments are routed to the various labs for repair or calibration.*

Source Well Room

Four calibration source wells are located in the calibration facility. The wells were designed for personnel safety, ease of use, and high throughput. Each well is 0.3 meters in diameter by 10 meters deep and contains a trolley-mounted, double-encapsulated radionuclide source. Trolley movement is controlled by a dedicated personal computer programmed to position the source for the desired exposure or dose equivalent rate at the top of the well (see Figure 2.15). Source-to-detector distances are automatically corrected to compensate for temperature, pressure, and source decay.

Figure 2.15. *Well Room with Three ^{137}Cs Wells (cylindrical shields; one not shown) and One ^{252}Cf Well (square block in back corner). The Well Room allows for rapid calibration of exposure rate instruments from about 0.1 mR/h to 17 R/h.*

Wells 1, 2, and 4 contain 0.30, 15.3, and 6.1 Ci of ^{137}Cs, respectively, and provide 662-keV photon fields from 50 mR/h to approximately 20 R/h.

Well 3 contains a 57-mCi source of ^{252}Cf, which provides neutron dose equivalent rates from 1 mrem/h up to 600 mrem/h for select neutron monitors. This well is calibrated specifically for each type of detector used to enable the accurate reflection of free-field conditions. Currently, it is configured for NRC AN/PDR-7O “Snoopy” and Eberline NRD-based detector reference to bare ^{252}Cf.

Together, the calibration wells make it possible to perform instrument calibrations and evaluations over a wide range of exposure rates with great accuracy, convenience, and speed of calibration and with minimum radiation exposure to the operator.

Survey Instrument Calibration Laboratories

The radiological instrument calibration facility is composed of six multi-purpose laboratories designed to provide the flexibility required to calibrate a wide range of portable and semi-portable radiological instrumentation and recertification of radioactive sources. Each laboratory is fully equipped with an assortment of the working standards necessary to perform NIST-traceable calibrations (Figures 2.16 and 2.17).

Figure 2.16*. Contamination Survey Instruments are Calibrated in Batches in a Dedicated Laboratory.*

In addition to the well sources and the High-Exposure Facility standards, more than 50 working standards are available, including a variety of low-activity alpha-, beta-, and gamma-emitting radionuclide sources that are recertified at least annually. Alpha sources available include ^{210}Bi, ^{226}Ra, ^{230}Th, ^{238}U, ^{239}Pu, and ^{241}Am. Beta sources available include ^{3}H, ^{14}C, ^{32}P, ^{36}Cl, ^{60}Co, ^{63}Ni, ^{85}Kr, ^{90}Sr/^{90}Y, ^{99}Tc, ^{106}Ru/^{106}Rh, ^{129}I, ^{137}Cs, ^{204}Tl, and a depleted uranium slab (Tables 2.1 through 2.4).

Figure 2.17. A Multi-purpose Laboratory. The Survey Intrument Calibration Laboratory provides space to calibrate a large variety of contamination survey intruments, sample counters, and particulate monitors.

Neutron sources in a low-scatter environment are available in three configurations:

♦ Bare ^{252}Cf	0.01 to 20,000 mrem/h
♦ D_2O moderated ^{252}Cf	0.05 to 5,000 mrem/h
♦ ^{241}AmBe	1 to 200 mrem/h

More than 50 different NIST-traceable x-ray beams (Tables 2.2, 2.3a, and 2.3b) in the energy range from 8 to 251 keV are available for special calibrations or testing.

The types of portable survey instruments calibrated in the laboratories include:

- Alpha and beta bench-top monitors/scalers.
- Area radiation monitors.
- Alpha and beta scintillation contamination hand-held meters.
- Air proportional hand-held contamination meters.
- G-M tube-based contamination and exposure rate hand-held meters.
- Ion chamber exposure-rate instruments.
- Micro-rem meters.
- Electronic and quartz fiber dosimeters.
- Tritium hand-held meters.
- Neutron exposure rate meters.

Personnel contamination monitors, hand and shoe monitors, portal monitors, road monitors, effluent alpha/beta, noble gas, and tritium monitors are calibrated at their field locations or in the calibration laboratory's climate-controlled garage.

Figure 2.18. Calibration of Alpha-Sensitive Continuous Air Monitors. They are calibrated in a dedicated laboratory, designed for efficient calibration of large numbers of instruments.

Continuous Air Monitor Calibration Laboratory

The Continuous Air Monitor (CAM) Facility contains space designed to calibrate alpha, beta, and alpha/beta CAMs (Figure 2.18). The laboratory is fully equipped with an assortment of the working standards necessary to perform NIST-traceable calibrations. The working standards include a variety of low-activity alpha and beta radionuclide sources that are recertified at least annually. The M&TE inventory includes pulsers, oscilliscopes, digital multimeters, pressure and vacuum gauges, and flowmeters, which are maintained and calibrated by an in-house metrology program. Computers, manufacturer software, and interface cables needed to support the computer-based instruments are also maintained.

Measuring and Test Equipment Calibration Laboratory

The M&TE Calibration Laboratory provides the flexibility to calibrate a wide range of physical and electrical instruments (Figure 2.19). The laboratory is fully equipped with a variety of NIST-traceable physical and electrical standards that allow for calibration of instruments that measure:

- voltage
- current
- resistance
- capacitance
- frequency
- temperature
- humidity
- dew point
- pressure
- vacuum
- gas flow
- pH
- conductivity
- time
- rotational speed
- wind speed

Calibrations are performed in accordance with established procedures and program requirements of ANSI/NCSL Z540-1 (1994).

Instrument Repair Shop

A complete instrument repair shop is located adjacent to the calibration facility (shown in Figure 2.20). The shop is fully equipped with the test equipment, tools, soldering stations, and machining equipment necessary to repair and maintain portable and semi-portable instruments to manufacturing specifications and standards.

The shop is stocked with an extensive supply of electronic components, switches, hardware, and radiation-detection-related parts. More than 8,000 repairs are made annually.

Figure 2.19. Calibration of Non-radiological M&TE. These instruments, such as digital volt meters, are calibrated in the ANSI Z540-compliant M&TE Calibration Laboratory.

Source Laboratory

The radioactive source recertification station is maintained in one of the calibration laboratories (Figure 2.21). The equipment, which meets the reference transfer instrument requirements of ISO-8769, consists of proportional detectors (window and windowless), counter/timers, and a multi-channel analyzer.

The recertification program is based upon direct comparison between the working standard and a reference source. Generally, the working standard and the reference source have identical radionuclides and similar geometries and construction. The uncertainty in the re-certifications is ±4% for contamination reference standards, ±5% for working standards, or ±10% for check sources at the 95% confidence level.

***Figure 2.20**. The 318 Building Radiological Calibration Facility. This facility includes an insrument repair shop that is staffed by three instrument tecnicians. The instrument repair shop maintains a spare parts inventory and the expertise to mainain and repair instruments calibrated by the Radiological Calibration Facility.*

Records Management and Web-Based Access

The Microsoft Access CalibrationDB software application is used to manage the calibration and repair business activities of the group. The database maintains a complete service history for each instrument in the inventory, covering calibration, repair, modification, instrument custodian, out-of-tolerance history, and reverse traceability. The software prints the calibration labels when requested by the calibration technician only after verifying that the technician is qualified to perform the applicable calibration. Replacement and spare parts inventory is managed with this system, with minimum and maximum quantities established by the engineering staff. For pool instruments, a quota system is used to manage a steady supply of instruments. Recall, overdue for calibration, and out-of-tolerance notifications are also generated. The recall notifications are sent via e-mail.

Web-based access to the CalibrationDB is available. From this website, customers may check on their quotas, obtain a list of instruments issued to their work location, create overdue calibration reports, obtain instrument history, and obtain a copy of delivery reports. General information about services and points of contact and forms helpful in conducting business are all available on the website.

Calibration certificates are digitally stored and managed on a TRIM Context® software-integrated platform from TOWER software. This software permits long-term storage of calibration records and is protected by routine back-ups. Records may be retrieved and sent to a client for electronic filing and storage.

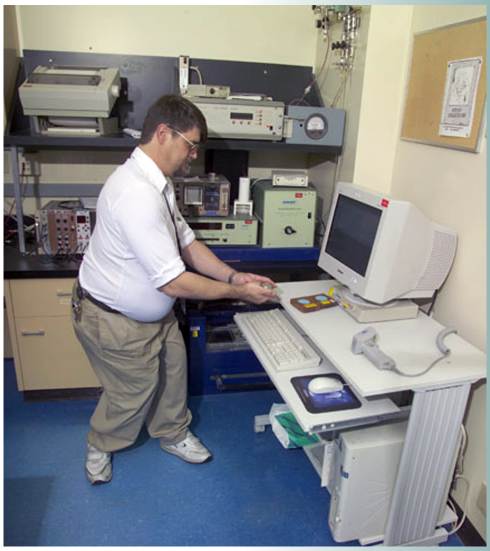

***Figure 2.21**. Radioactive Source Recertification Station. Alpha- and beta-emitting radioactive sources are recertified by comparing their emission rates to identically constructed reference sources.*

2.3 Environmental Effects Laboratory

Figure 2.22. *Environmental Chamber. This is one of two environmental chambers used by PNNL to evaluate instrument response to extreme temperatures and humidities. The range of the Russells chamber (shown) is -68°C to 177°C; 5% to 95% RH. The Tenney Chamber (not shown) has a range of -20°C to 60°C; 5% to 95% RH.*

In addition to routine calibration and evaluation capabilities, the Radiological Standards and Calibration Laboratory also possesses specialized testing capabilities supporting controlled, operational evaluations of health physics instrumentation, performed in a wide range of conditions (e.g., ANSI N42.17A [ANSI 1989a], ANSI N42.17C [ANSI 1989b], ANSI N42.32 [ANSI 2003], and ANSI N42.33 [ANSI 2004]). PNNL designed this fully operational laboratory to characterize the effects of temperature, pressure, humidity, vibration, acceleration, AC power, and microwave, radiofrequency (RF), and electromagnetic fields on a variety of instrumentation. These capablilities are routinely used to type-test new instruments.

Environmental Chambers

Environmental chambers support temperature and relative humidity (RH) ranges of -70°C to 170°C and 5% to 95% RH (see Figure 2.22). The chambers can also generate condensing environments.

A walk-in chamber provides a test volume of 4.2 m^3 and a second chamber has a test volume of 0.4 m^3. A pressure/vacuum chamber simulates atmospheric pressure from 26 to 370 kPa (see Figure 2.23).

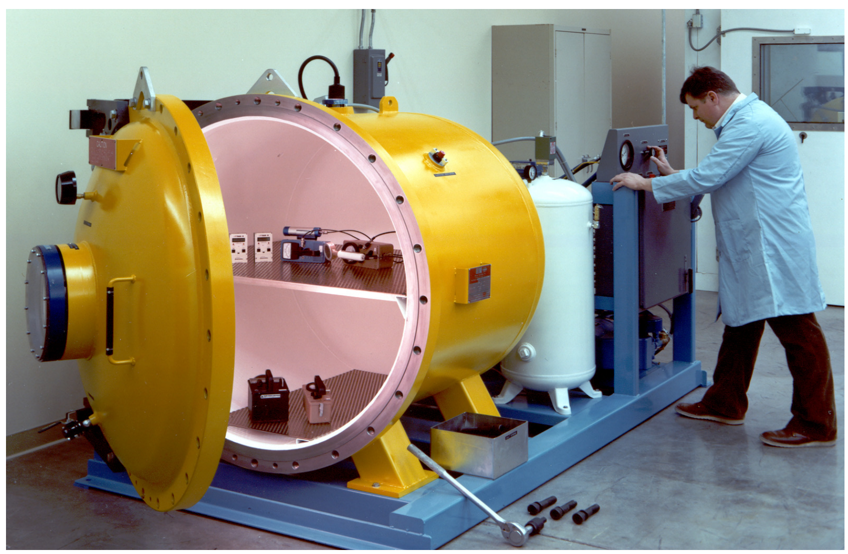

Figure 2.23. *Pressure/Vacuum Chamber for Simulating Variations in Ambient Pressure Levels (volume: 1.4 m^3; range: 26 kPa to 370 kPa)*

Mechanical Testing

Two vibration tables permit instrument performance evaluation after and during mechanical vibrations over a wide range of conditions. An electrodynamic vibration table supports payloads up to 45 kg (100 lb) over the frequency range of 10 to 5000 Hz to a maximum acceleration of 1 G, or smaller payloads up to a maximum acceleration of 10 G (Figure 2.24). A computer controller can generate high-range, random vibrations. A larger vibration table supports payloads up to 680 kg (1500 lb) and a maximum acceleration of 3.2 G over the frequency range of 8 to 60 Hz (Figure 2.25).

Non-Ionizing Radiation Environments

A variety of field-generating equipment measures effects from interfering non-ionizing radiations. A microwave exposure chamber generates fields at 2450 MHz with a field strength of up to 20 mW/cm^2. A magnetic exposure chamber generates fields of 0 to 10 gauss DC or 60 Hz (Figure 2.26) within a volume of 1 ft^3.

Electrostatic Discharge Susceptibility

An electrostatic test system provides a 0 to 25,000 V discharge in contact mode. Voltage is continuously adjustable and can be set to several discharge rates.

Figure 2.24. *High-Frequency, High-Acceleration Vibration Table. Up to 100 lb may be tested at up to 10 G over the frequency range of 10 to 60 Hz.*

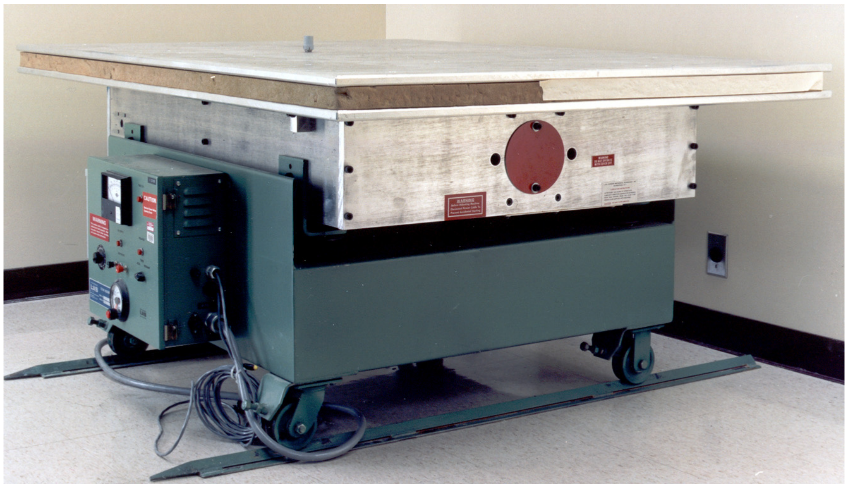

Figure 2.25. *Mechanical Vibration Table (frequency range: 8 to 60 Hz; maximum acceleration: 3.2 g; maximum test load: 680 kg)*

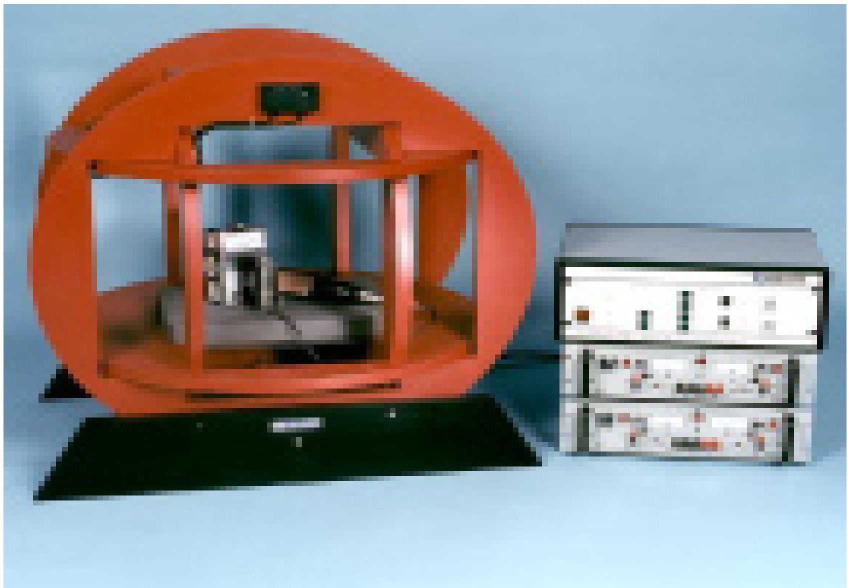

Figure 2.26. *Magnetic Field Exposure System (DC and 60 Hz; range: 0 to 10 Gauss)*

AC Power and Line Noise Susceptibility

Power-line test equipment generates variations in power-line voltage and frequency over the voltage range of 0 to 125 V (or 0 to 250 V) in the frequency range of 20 to 2,000 Hz. The equipment can produce voltage sags and surges of ±5% of the power supply frequency. To simulate large transients (e.g., lightning strikes), a transient generator can generate ring wave and bi-wave transients meeting specifications of ANSI/IEEE C62.41 (1991).

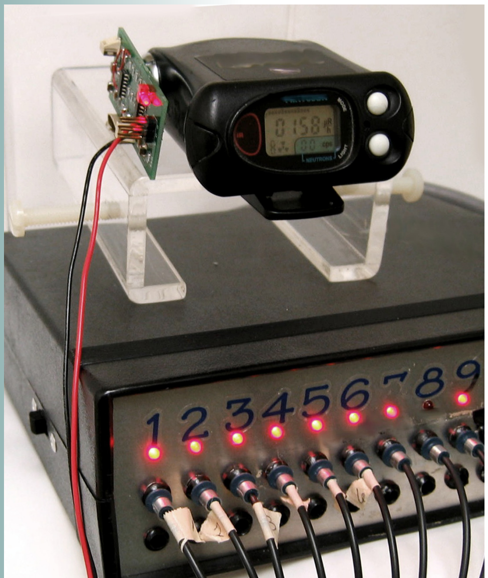

Figure 2.27. *Precision Measurement of Instrument Response Time. Precise measurements of an instruments response time to changes in radiation intensity are made using a custom circuit that converts the instrument's audible or visual response to a digital signal.*

Response to Dynamic Radiation Fields

Two systems allow the evaluation of effects from changing radiological conditions. A computer-controlled rail system provides an automated, repeatable increase in radiation field strength (Figure 2.27). The system has a maximum speed of 5 m/s and can move objects of up to 1 kg. Control parameters include acceleration, speed, and deceleration along the length of the track. Automated acquisition can be employed to facilitate unattended data collection and processing. A second system acquires similar data, but provides for a nearly instantaneous increase in the radiation level. This instrument evaluates effects from a sudden change in the radiation intensity.

2.4 Dosimetry Laboratory

The External Dosimetry Laboratory at PNNL is a large-capacity laboratory that provides personnel, environmental, and nuclear accident dosimetry services for PNNL and the DOE's Hanford Site, as well as other DOE sites and private sector clients. The laboratory has capabilities in thermoluminescent dosimetry (TLD), electrochemically etched track dosimetry, and nuclear accident dosimetry by activation analysis of foils, sulfur pellets, and biological samples. The laboratory is managed by the Hanford External Dosimetry Program, which has been accredited in personnel dosimetry by the DOELAP since 1989. The laboratory maintained accreditation with the NVLAP from 1997

Figure 2.28. *The Harshaw 8800 Reader. The dosimeters are "read" by heating each of the four TLD chips on the TLD card according to a programmed time-temperature profile. The light emitted from the chips is proportional to the radiation dose received and is measured with low noise photomultiplier tubes.*

to 2003, when accreditation was voluntarily discontinued for business reasons. The laboratory complies with all relevant aspects of ISO-17025 (ISO 1990).

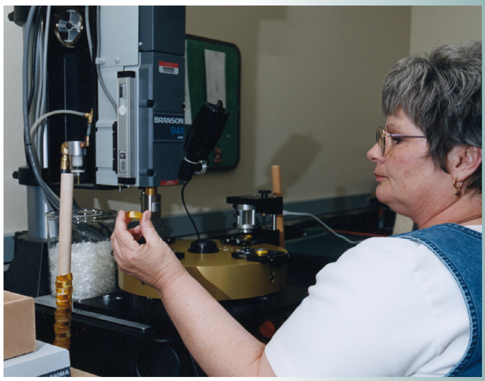

Figure 2.29. Ring Sealer. Two rings are available for use. The Global Dosimetry Solutions hard plastic ring is shown being sealed for use after the single TLD chip and permanent bar code have been loaded into the ring. The Harshaw EXT-RAD is the finger ring used for non-government customers.

The laboratory houses four Harshaw Model 8800 TLD readers (Figure 2.28), two Harshaw Model 6600 TLD readers, a Harshaw Model 5500 TLD reader, as well as TLD annealing ovens, track etch ovens, electrochemical etch chambers and track counting equipment, ultrasonic welding equipment for ring sealing (Figure 2.29), and ultrasonic cleaning equipment for dosimeter cleaning. Most types of commercially available TLDs and phosphors can be and have been processed by the laboratory. Glow curves are monitored to ensure accurate phosphor heating and peak integration. Phosphors are annealed in an atmospherically controlled oven for preset time and temperature conditions. Special annealing techniques are used to allow for annual exchange frequency for whole-body dosimeters. Laboratory lighting and temperature are regulated to minimize potential external sources of non-radiation-induced noise to the radiation-induced signal in the different phosphors. Linearity, uniformity, reproducibility, detection threshold, fading, energy dependence, and response to environmental influences have been determined for all dosimeter types in inventory.

Personnel dosimetry capabilities include large-scale dosimetry services using ^{7}LiF:Mg,Ti (TLD 700) and ^{6}LiF:Mg,Ti (TLD 600) phosphors. The Harshaw 8825 beta-gamma-neutron dosimeter has been accredited in all DOELAP and NVLAP test categories. The Harshaw 8816 neutron dosimeter is a dedicated neutron dosimeter that contains three TLD 600 elements and one TLD 700 element. The unique arrangement of cadmium filters for the Harshaw 8816 provides two independent element ratios for a neutron-energy discrimination capability. This dosimeter is used to supplement a beta-gamma dosimeter in environments where neutron-energy discrimination is needed for greater accuracy. The Harshaw 8816 neutron dosimeter is used at Hanford to monitor individuals working in a wide variety of neutron spectra using a single algorithm. With suitable multisphere or tissue-equivalent proportional counter field measurements, energy-discriminating TLD-based algorithms can be developed for use with this dosimeter in most environments.

In addition to TLD cards, the Harshaw 8816 dosimeter holder is also designed to hold two optional CR39 track etch foils. When used, the foils can be electrochemically etched to provide accurate neutron dosimetry in high-energy applications and in unknown moderated fields down to 100 keV (Figure 2.30). Several types of extremity dosimeters using TLD 700 and TLD 600 phosphors have been developed and accredited for use at Hanford and other DOE sites.

Environmental dosimetry capabilities include TLD services using the Harshaw 8807 environmental dosimeter. This dosimeter contains ^{7}LiF:Mg,Ti, and CaF_2:Dy phosphors. Dosimeters using the high-sensitivity phosphors Al_2O_3:C and LiF:Cu,P have also been characterized and developed for special applications requiring low-dose measurements with high precision. The Al_2O_3:C TLDs are capable of measuring doses less than 0.01 mSv with a precision of 10% or better and are suitable for special applications requiring in situ measurements on a daily or weekly basis.

PNNL capabilities in nuclear accident dosimetry include personal nuclear accident dosimeters (PNADs) and fixed nuclear accident dosimeters (FNADs) that use a combination of TLD chips, neutron activation foils, and sulfur pellets. Both dosimeters measure neutron and gamma dose and meet DOE requirements for range and accuracy. Performance of these dosimeters has been demonstrated in two criticality dosimetry intercomparisons conducted by DOE. Procedures have also been developed to support direct and indirect bioassay methods for criticality neutron dosimetry.

The External Dosimetry Laboratory staff provides capabilities in field measurements, dosimeter design, algorithm development, performance testing, and specialized field applications. The staff has experience in characterizing beta and neutron fields and associated dosimeter responses in the workplace to develop facility-specific algorithms or to verify dosimeter performance in the workplace. Work has also been performed to characterize beta and photon laboratory sources in terms of deep dose gradient, irradiation field uniformity, and energy spectra. The laboratory supports Hanford decontamination and decommissioning (D&D) activities with specialized in situ measurements of piping, tanks, sumps, wells, and other difficult-to-access locations, using TLD trees and specialized probes for hand-held survey instruments. Specialized TLD arrays have been provided for dose mapping of beams for both operational and D&D activities. The TLD provides services to satisfy multiple program needs at Hanford and other sites.

Figure 2.30 *Track-Etch Dosimeter (TED) Reader. TED foils can be included as one component of the neutron dosimeter, or can be used for special neutron dosimetry projects. The foils are small sheets of CR39 polycarbonate plastic. When neutrons strike the plastic, they leave microscopic tracks. These tracks are enlarged by electrochemical etching and then counted using a microscope with a camera attached. Image-recognition software designed at Battelle "recognizes" and counts the tracks in each filed which is directly proportional to the neutron dose received.*

2.5 Medical Seed Characterization

There is an increasing need for calibrations of medical radiation sources (Fig. 2.31) and instruments. NIST currently performs many such calibrations, but is committed to transferring this work to accredited dosimetry calibration laboratories (ADCLs). To build this capability, PNNL acquired equipment similar to that used at NIST and at some ADCLs and universities, including solid water phantoms, TLD microcubes, a TLD reader, a vacuum needle, a film scanner imaging system, and radiochromic film. This equipment allows PNNL to perform measurements defined by the accrediting organization in the brachytherapy industry, the American Association of Physicists in Medicine (AAPM). In particular, the evaluations provided are defined in the AAPM Task Group 43 dosimetry protocol, “Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group No. 43” (*Med. Phys*. 22, pp. 209-233, 1995). These evaluations include air-kerma strength ($\mu Gy\ h^{-1}\ m^2$); absorbed dose rate (cGy/h) in water at distances from 0.5 to 9 cm; dose rate constant, Λ ,which is in units of $cGy\ h^{-1}U^{-1}$ and is obtained from the ratio of the absorbed dose rate in water (at the reference point r = 1 cm, θ = 90 degrees) to the air-kerma strength; geometry factor, G(r,θ), which accounts for the variation of relative dose due only to the spatial distribution of activity within the source; radial dose function, g(r), which accounts for the effects of absorption and scatter in the medium: $g(r) = D(r,\theta_o)\ G(r_o,\theta_o)\ /\ D(r_o,\theta_o)\ G(r,\theta_o)$; and anisotropy function, F(r,θ), which accounts for the anisotropy (non-uniformity) of dose distribution around the source: $F(r,\theta) = D(r,\theta)\ G(r,\theta_o)\ /\ D(r,\theta_o)\ G(r,\theta)$.

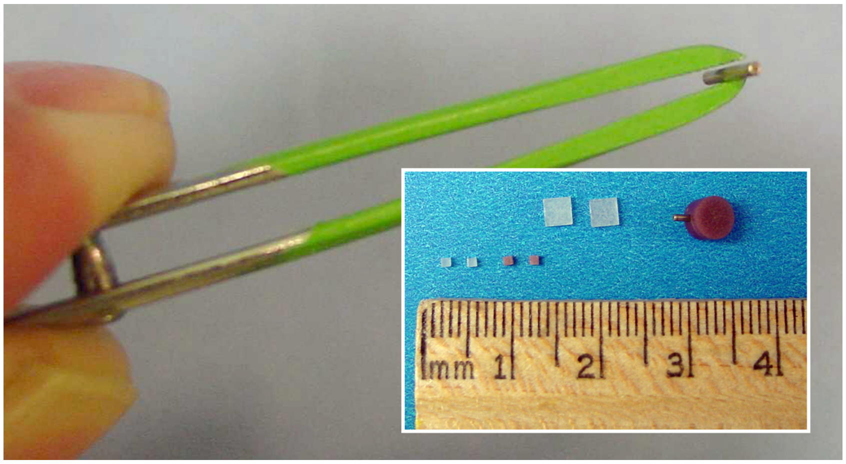

Figure 2.31 *Radioactive seeds used to treat cancer patients are characterized in the medical seed laboratory. Very small thermoluminescent chips (inset) are used to characterize radiation dose from the seeds.*

These evaluations can be performed for all the various types of brachytherapy seeds on the market, including x-rays and beta-emitters. Additional measurements that can be performed on these seeds include energy spectra and half-life.

3.0 In Vivo Radioassay and Research Facility

The In Vivo Radioassay and Research Facility (IVRRF) houses the unique equipment and instrumentation designed specifically to detect and quantify the amounts of radioactive material in the body. The majority of the work at IVRRF involves measurements of radiation workers from the DOE's Hanford Site under the auspices of the In Vivo Monitoring Program (IVMP). However, work is also performed for non-DOE clients. We have the capacity to perform large numbers of measurements on a routine basis. Currently, 6,000 to 7,000 worker measurements are performed annually, in addition to a minimum of 2,500 quality control measurements. There is additional capacity to perform up to 15,000 worker measurements annually.

The IVMP at Hanford was one of the first programs to be accredited under the DOELAP. Formal accreditation under DOELAP began in 1998 and reaccreditation is required every three years. This requires the program to pass rigorous performance tests in six measurement categories currently and to satisfactorily complete an onsite assessment conducted by DOELAP assessors.

The 747A Building located in downtown Richland, Washington, houses the IVRRF. The facility contains five heavily shielded counting rooms: the Iron Room, the Palmer room, the Stainless Steel Room, and two lead-shielded rooms (the Standup Counter and the Lead Room). These facilities are used to perform in vivo measurements of radioactive materials in the human body. Several of the rooms are equipped with specialized detectors for measuring radioactive materials such as low-level photons in the lungs or radioiodine in the thyroid.

3.1 In Vivo Counting Equipment and Instrumentation

The IVRRF houses five shielded in vivo counting systems with filtered ventilation systems. The shielding and ventilation are used to reduce the environmental background radiation levels from cosmic, terrestrial, and airborne sources. Three of the rooms are shielded with pre-World War II steel from the hulls of decommissioned battleships. A graded shield composed of thin layers of lead, cadmium, tin, copper, or stainless steel is used on the interior walls of the rooms to absorb low-energy photons generated from the absorption of high-energy cosmic and terrestrial radiations in the steel. Two other counting systems are shielded with lead to reduce the environmental background levels. Table 3.1 contains minimum detectable activities for these systems.

There are four routinely used counting systems and several less frequently used systems. The two primary whole-body counting systems are designed to detect and quantify radionuclides (e.g., ^{137}Cs, ^{60}Co, and ^{154}Eu) that emit photons with energies greater than 200 keV. One whole-body counting system uses an array of five large NaI detectors and is used as a screening counter. The other system is a scanning arrangement that employs five coaxial high-purity germanium (HPGe) detectors. The four routine counting systems are accredited through DOELAP.

Table 3.1. Typical Minimum Detectable Activities (MDA)

Nuclide	MDA (nCi)
50-min Chest Count	
^{241}Am	0.15
^{234}Th	1.5
^{235}U	0.09
3-min Standup Whole Body Count	
^{137}Cs	1.3
10-min Coaxial Germanium Whole Body Count	
^{137}Cs	0.80
^{154}Eu	1.7

Palmer Room

The Palmer Room measures 2.5 x 3.7 x 2.4 meters, with the walls, floor, and ceiling made of 30-cm battleship armor plate from the U.S.S. Indiana. The interior surfaces are lined with a graded shield of thin layers of lead, cadmium, and copper.

A five-detector array of large-volume (120%) coaxial germanium detectors is installed in the room and is used primarily for whole-body measurement of gamma ray energies above 200 keV. The system can be operated in a geometry-independent scanning mode or a more geometry-dependent stationary mode (see Figure 3.1). The output from each of the detector preamplifiers is routed to a digital signal analyzer (DSA), which is a multichannel analyzer (MCA) combined with subsystems needed for spectral acquisition, including a digital signal processor, high-voltage power supply, digital stabilizer, MCA memory, and network interface. Acquisition and analysis of the spectral data for all counting systems is controlled from an Alphastation workstation running the Abacos Plus software from Canberra Industries. The Alphastation is interfaced with the DSA units (as well as the other counting systems) via a local area network. The spectral analysis includes a robust peak search algorithm to identify nuclide peaks and a nuclide-library-based computation to quantify activities.

The Palmer Room is named for Earl Palmer, who managed the program from 1970 to 1990. Earl was instrumental in the development of high-efficiency sodium iodide and HPGe systems for in vivo measurements at Hanford. Earl also made significant contributions to improving the measurement of plutonium and other transuranics in the body.

***Figure 3.1**. Coaxial HPGe Detectors in Palmer Room*

Standup Counter

Figure 3.2. Standup Counter Detectors

The standup counter (Figure 3.2) is shielded with 10-cm-thick lead brick and is designed for a subject to stand upright with his or her back to the detectors to have a quick measurement performed. The counter has a shielded maze entrance that allows only unscattered photons from the subject to reach the detectors. The detectors are positioned on a frame that can be adjusted vertically, depending on the subject's height. This counter is used to perform screening measurements for fission and activation products. If the standup counter results exceed the decision level, measurements are made with the coaxial HPGe system to positively identify the nuclide and quantify the activity.

Iron Room

The Iron Room houses one of two lung counting systems. The system is composed of an array of four 38-cm^2 planar HPGe detectors and associated electronics. The design optimizes the detection efficiency for measurement of low-energy photons (<200 keV) emitted by radionuclides such as ^{239}Pu, ^{241}Am, ^{nat}U, and ^{235}U.

The Iron Room measures 2.7 x 3.0 x 2.3 meters, having 25.4-cm-thick hardened iron armor plate walls, ceiling, and floor. The inner lining of the room consists of a graded shield of 3.2-mm lead, 0.5-mm cadmium, and 1.5-mm copper to further reduce the background radiation intensity at low energies. The outputs from the four detectors are combined for the final data analysis, but the spectral data from the individual detectors are also saved. Results are routinely calculated for ^{241}Am, ^{234}Th, and ^{235}U. The efficiency calibrations at the particular energies are calculated as a function of the thickness of the chest.

The iron for the Iron Room shield walls came from a battleship built prior to World War II. Because the ship was built before the war, the iron is free of fallout contamination, and provides a low background counting environment.

Stainless Steel Room

The second lung-counting system is housed in the Stainless Steel Room (Figure 3.3). It also contains an array of four 38-cm^2 planar HPGe detectors similar to the Iron Room. The Stainless Steel Room, named for its stainless steel interior surface, measures 2.9 x 3.0 x 2.2 meters. It has a 30-cm-thick iron wall in common with the Palmer Room, a 25.4-cm-thick iron wall in common with the Iron Room, and two 19-cm-thick iron walls that were obtained from the Nevada Test Site. The floor and ceiling are composed of a 12.5-cm-thick iron armor plate and 10 cm of lead brick. This room also has a graded shield composed of 0.318 cm of lead, 0.159 cm of tin, and 0.159 cm of stainless steel. Tin replaced cadmium for cost purposes, and stainless steel replaced copper for its better wear properties. Background measurements taken in the room indicated that this type of shielding is equivalent to the Iron Room shielding. The outputs from the four detectors are routed to individual digital signal processors, which are similar to the DSA units used in the Palmer Room but of an earlier design. As is done in the Iron Room, the calculations are based on the summation of the four signals, but the individual detector spectra are also retained.

Lead Room

A fifth room, the Lead Room, has 10-cm-thick lead walls, ceiling, and floor composed of virgin lead bricks that are covered by a 1.0-mm layer of copper. The room is 2.85 x 2.34 x 2.08 meters. Arrays of planar germanium detectors are used in this room to measure transuranic elements, uranium, and other low-energy photon-emitters. Arrays of NaI detectors can be configured in a bed arrangement for measurement of high-energy photons. Currently, the room is used primarily for measurements of ^{235}U in the lungs. This system is not DOELAP-accredited and is used for non-DOE clients.

***Figure 3.3**. Typical Detector Arrangement. The detector arrangement shown is typical of the four detector arrays used in the Iron Room and Stainless Steel Room.*

3.2 Calibration Phantoms

The IVRRF measurement systems are calibrated to convert a measured count rate in a specific energy region to an estimate of the corresponding activity. This is accomplished through the use of calibration factors derived from measurements of anthropometric phantoms. Measurements of the phantoms are made and the efficiency in terms of count rate per unit activity is calculated for the energy range of interest. For lung counting, the efficiency is calculated at specific energies as a function of the chest thickness.

Several types of calibration phantoms are used to simulate the characteristics of the body. Torso phantoms are used to provide detailed simulations of the body shape and size from the shoulders to the hips. The torso phantom is modeled from a cadaver that was chosen to be representative of a reference male. Organ inserts (e.g., lung, liver) containing the radioactive material are placed in the torso. The phantom composition closely simulates the radiation interaction properties of the tissues in the body for energies as low as 17 keV. The torso phantoms include chest overlays that allow calibration factors to be calculated as a function of the tissue thickness over the lungs (Figure 3.4).

Bottle manikin absorption (BOMAB) phantoms are composed of 10 polyethylene containers that when assembled simulate the body's size and shape. The containers can be filled with tissue substitute polyurethane or an aqueous solution that contains the radioactive material uniformly distributed in the volume. The BOMAB phantoms (Figure 3.5) are used to calibrate the whole-body counting systems.

Figure 3.4. *Torso Calibration Phantom. The photo shows lung phantoms within the torso (center) and chest overlays to simulate varying chest thickness (left).*

Thyroid, bone, liver, and wound phantoms are also used to calibrate the counting systems to allow estimates to be made of the activity present in these organs and tissues. The calibration phantoms used by the IVMP are part of the DOE Phantom Library and are made available for loan to other in vivo counting facilities upon request.

Staff at PNNL can fabricate the organ inserts for torso phantoms and polyurethane filler for the BOMAB phantoms. The unique tissue substitutes are formulated to have attenuation coefficients modeled after values published by the International Commission on Radiation Units and Measurements in Publications 44 and 48 (ICRU 1989, 1992). The tissue-substitute materials used to simulate the tissues and organs contain radioactive materials in a uniform distribution. The laboratory also provides the calibration lung phantoms for DOELAP for radiobioassay and has provided many government and private customers with customized calibration phantoms.

A semi-trailer, which houses a horizontal shadow shield counter, a vertical shadow shield counter, and a shielded cave, is available for onsite or offsite deployment. The shadow-shield systems use NaI detection and are designed primarily for the measurement of fission and activation products. However, HPGe detectors can also be installed and used for applications where sensitivity is not critical.

Figure 3.5 *Bottle Manikin Absorption Phantom*

Phantom Library

PNNL operates the DOE Phantom Library program for the DOE Office of Quality Assurance Programs, EH-31, out of the IVRRF. The program loans in vivo calibration phantoms to DOE sites and other in vivo laboratories. The inventory of the library includes BOMAB phantoms, a fission product phantom, realistic torso phantoms with various tissue-equivalent organ inserts, thyroid phantoms, and a ^{241}Am skeletal phantom. Additional information on the Phantom Library can be found at http://www.pnl.gov/phantom/.

4.0 Non-Destructive Analysis Program

The PNNL NDA Program performs diverse measurements of radioactive and nuclear materials. The program is designed to perform in many applications including:

- Waste container characterization of all sizes from small vials to large cargo containers.
- Assessment of material holdup in process equipment such as glove boxes, fume hoods, pipelines, ductwork, plenums, and high-efficiency particulate air filters.
- Confirmatory and verification measurements of special nuclear materials for safeguards purposed.
- Quantifying fissile materials for criticality safety purposes.
- Measurements of environmental media such as soil for characterization and scoping activities.

Depending on the task specifics our NDA team uses a combination of state-of-the-art measurement instruments and modeling and calculation techniques. The team also has highly trained and experienced staff available for consultation, independent technical reviews, and other intellectual assistance.

Mobile NDA Instruments include:

- Several Canberra In Situ Object Counting Systems with HPGe detectors. These versatile gamma-spectrometry systems can fit many field applications.
- Multigroup Analysis and PC FRAM software are applied for plutonium and uranium isotopic analysis.
- Several neutron slabe detectors calibrated for measurements of many objects of various dimensions.

These measurement systems can be quickly delivered and employed using our Mobile NDA Trailer. This trailer is used for transporting the equipment essentially anywhere and is also used as an office space for the NDA staff and computers while performing field measurements. The trailer is equipped with a propane powered generator and can generate its own power supply if necessary. The powerful tandem of the mobile NDA instruments and trailer equip our NDA team with all the tools necessary to quickly respond to virtually any onsite application, including a backup emergency mobile laboratory for DOE Region 8 emergency response.

Transportable Equipment is usually used in the NDA laboratory in the 325 Building, but can be transported to a client's specified location (Figure 4.1). These systems include:

- Automated segmented gamma scanning and neutron coincidence counting system used to characterize 55-gallon drums of low-level or transuranic waste.
- Well neutron coincidence counter designed for passive measurements of plutonium-bearing materials and active interrogation assay of enriched uranium. The counter is primarily used for safeguards applications.

Figure 4.1. *Portable Neutron Slab Detector. PNNL's portable NDA systems are readily deployable to field locations for counting difficult-to-move objects (such as the standard waste box shown here) or to perform hold-up measurements.*

A variety of Reference Materials (RM) is essential for the proper calibration and performance checks of any measurement equipment. The NDA Program possesses several sets of NIST-traceable RMs spanning a wide range of isotopic composition and masses.

Nationally recognized technical expertise is provided by the NDA staff that includes scientists, well-trained and seasoned technicians, and an experienced program manager that share more than 50 years of onsite and international experience in the field. The team is experienced in solving challenging measurement problems including demanding sensitivity requirements and unusual geometries.

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