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American National Standard Performance Criteria for Instrumentation Used for Inplant Plutonium Monitoring

Secretariat for N42

Institute of Electrical and Electronics Engineers, Inc

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Health Physics Society

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Foreword

(This Foreword is not a part of ANSI N317-1980 American National Standard Performance Criteria for Instrumentation Used for Inplant Plutonium Monitoring.)

This standard was prepared under the joint sponsorship of the American National Standards Committee on Instrumentation, N42, and the American National Standards Committee on Radiation Protection, N13. The members of both N42 and N13 reviewed and approved this standard.

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American National Standard Performance Criteria for Instrumentation Used for Inplant Plutonium Monitoring

1. Introduction

The monitoring of plutonium requires special instrumentation considerations in order to achieve optimum measurement performance. Performance specifications consistent with current state-of-art instrumentation technology is provided in this standard and is applicable to plutonium handling and storage facilities, excluding reactors and irradiated fuel reprocessing facilities.

2. Scope

Performance criteria for radiation protection instrumentation essential to inplant plutonium monitoring is defined in this standard and its appendix. Plutonium radiations are also characterized here. Performance criteria established in this standard are limited to instruments capable of measuring (1) photon radiations within the energy range of 0.010 to 1.25 MeV, (2) neutron radiations within the energy range from thermal to 10 MeV, and (3) alpha radiations within the emitted energy range of 4.5 to 7.5 MeV.

This standard does not apply to the construction of specific instruments nor does it specify instrumentation to be employed for each survey to be conducted, other than in generic terms. This standard does not define specifications for personnel dosimeters, effluent monitoring systems, or instruments needed in bioassay programs, nor does this standard define those requirements which may be needed to monitor emergency conditions.

Throughout these criteria, two verbs have been used to indicate the degree of rigor intended by the specific criterion. *Shall* indicates a minimum criterion that must be met, while *should* indicates a criterion that is recommended as good practice and is to be applied when practical.

3. Definitions

Use of technical terminology within this standard is generally consistent with the definitions in the American National Standard Glossary of Terms in Nuclear Science and Technology, ANSI N1.1-1976 [1][1] and ICRU Report 20 1971 [2]. The following terms are defined specifically for use within this standard.

accuracy. The degree of agreement with the true value of the quantity being measured.

calibrate. To determine the response or reading of an instrument relative to a series of known radiation values over the range of the instrument.

extracameral response. An instrument response arising from the action of the radiation field on parts of the instrument other than the intended radiosensitive element.

instrument. A complete system designed to quantify a particular type of ionizing radiation.

national standard. An instrument, source or other system or device maintained and promulgated as such by the US National Bureau of Standards.

operating range. The region between the limits within which a quantity is measured.

precision. The degree of agreement of repeated measurements of the same property, expressed quantitatively as the standard deviation computed from the results of the series of measurements.

readout. The device that conveys information regarding the measurement to the user.

[1]Numbers in brackets correspond to those in Section 6 of this standard.

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resolution. The minimum detectable change in instrument response.

surface contamination. Radioactive material deposited on the surface of facilities (floor surfaces, workbench tops, machines, etc), equipment, or personnel.

survey. The examination of an area for the purpose of detecting the presence of radioactive materials and determining the quantity of that radioactivity.

survey contamination control. A survey conducted to determine the presence of unwanted contaminants, normally conducted with alpha or gamma, or both, sensitive instruments.

survey dose rate. A survey conducted to determine the dose rate at some specified location or area and usually conducted with gamma exposure rate survey instruments. Neutron surveys may also be required frequently.

4. Plutonium Monitoring and Calibration Considerations

The radiations resulting from the radioactive decay of *plutonium* are varied and include alpha, beta, gamma, x-rays and neutrons (See Appendix A). An effective monitoring program for *plutonium* requires instruments that are responsive to these radiations with the exception of the 7 keV $\bar{E}$ beta resulting from the decay of ^{241}Pu.

In most instances contamination control surveys require alpha sensitive instruments. Exposure rate surveys would normally be conducted with photon sensitive instruments with known energy responses down to and including 0.010 MeV. Neutron surveys become important when processing tens of grams of ^{238}Pu or hundreds of grams of mixed isotopes of plutonium, particularly plutonium compounds (for example, PuO_2, PuF_4, etc). This is possibly the only survey of importance when photon shields such as leaded glass are employed. The use of such shields normally stops all of the charged particles, most of the low energy photons and essentially none of the neutrons. Under these circumstances, neutron radiation is likely to be the major contributor to personnel exposure.

Under certain conditions the extremities and forearms of personnel working with plutonium (and other radioactive materials) in glove boxes are exposed to the various types of radiations mentioned above. Generally, socalled *contact dose rates* are established to control the exposure to the workers' hands. No such measurement is currently made to determine the neutron *contact* dose equivalent rate because there is no suitable instrument available to perform the measurement. However, an estimate of the neutron dose equivalent could be made and could be added to the other measurements for exposure control purposes. Californium–252 is suggested for use as the calibration source because its neutron energy distribution is similar to that of plutonium metal and PuO_2 [3].

5. Instrument Performance Criteria

Instrument performance criteria are presented here for portable survey instruments and for fixed monitoring instruments.

5.1. Portable Survey Instruments, General Criteria. Inplant plutonium monitoring programs consist mainly of airborne and surface contamination surveys and dose rate surveys. General performance criteria for instrumentation needed to conduct these programs are described below.

5.1.1. Detection Capability

(1) Except as otherwise specified in this standard, the overall instrument accuracy shall be within ±20% and the precision within ±10% at the 95% confidence level for any single measurement. The ±20% and ±10% figures shall apply over the entire operating range for both logarithmic and linear scales except that for linear scales they need not be better than ±5% of full scale.

(2) Overall instrument response time (0 to 90% of full scale reading), after a 1 min warm-up, shall be $\leq$10 s on the most sensitive ranges and $\leq$2 s at readings of 100 mrem/h, 100 mR/h and 500 disintegrations per min or greater. This does not preclude the inclusion of variable response time capability. Response time to a decreasing field (full reading to 10% of original reading) shall be no greater than response times to increasing fields.

(3) Stability shall be evidenced by the ability of the instrument to maintain accuracy and precision for at least 24 h of continuous duty after initial warm-up.

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(4) Resolution shall be $\leq$4% of full scale for a linear scale and $\leq$8% of a reading for log scale with a maximum of two decades per 90° of meter movement.

(5) Extracameral responses should be undetectable in 1.25 MeV photon fields with an intensity of 20 R/h and 2 MeV (E_{max}) beta fields providing an air dose of 10 rd/h.

5.1.2. Readout, Power, and Response Requirements

(1) The readout should be illuminated to permit use in darkness; luminous or lighted dials should be considered.

(2) A 10 mV or 1 mA recorder output should be provided for instruments which are to be used with a recorder.

(3) The instrument should be powered by readily available cells or batteries such as AA, C or D cells or 9 V batteries. Compatibility with alkaline, Ni-Cd or mercury cells should be considered. Provision for operation from a standard automobile 12 V system and 117 V, 60 Hz, alternating current also should be considered.

(4) Minimum battery lifetime shall be 200 h of continuous duty operation at an exposure level of 10% of the maximum full scale reading at temperatures above 0 °C. Alkaline batteries shall be used for temperatures below 0 °C, and the minimum battery lifetime shall be 100 h of continuous operation.

(5) The instrument shall be equipped with a battery check switch and indicator of battery condition.

(6) When responding to levels in excess of the maximum range the readout shall remain full upscale.

5.1.3. Response to Environmental Factors

(1) The instrument shall operate within specifications for the temperature extremes anticipated.

(2) For the anticipated operation at temperature range the temperature coefficient shall be $\leq$0.5% per °C. The variations with temperature over the anticipated operating range should not produce a deviation of more than ±15% from the reference value obtained at 20 °C.

(3) The instrument system shall function within specifications over all anticipated combinations of temperature and humidity. (Testing will normally be conducted at a relative humidity within the range of 40% to 95% over a temperature range of 15 °C to 65 °C. The instrument system shall continue to operate properly after being cycled through the dewpoint at 20 °C ± 10 °C.

5.2 Portable Survey Instruments, Specific Criteria. Specific criteria are presented here for alpha, photon and neutron survey instruments.

5.2.1 Alpha survey instruments shall meet the following performance criteria:

(1) The minimum detection capability for alpha surface contamination should be 220 disintegrations per min/100 cm^2 of surface area and shall be not more than 500 disintegrations per min/100 cm^2, within the accuracy specified in 5.1.1. This requirement shall be met in the presence of a radiation field of 0.10 rem/h of neutrons in the energy range of thermal to 10 MeV, in the presence of 0.10 rem/h, or in the presence of both, of photons in the energy range of 0.010 to 1.25 MeV.

(2) The operating range of the instruments should be from 0 disintegrations per min to at least 100 000 disintegrations per min/100 cm^2 of surface area.

5.2.2 Photon survey instruments shall meet the following performance criteria:

(1) Instruments shall meet accuracy requirements in the energy range of 0.01 MeV to 1.25 MeV.

(2) Angular dependence for photon measurement instruments should be within ±15% over a 2π steradian frontal direction using at least two photon sources with energies of 0.06 to 1.25 MeV.

(3) Energy dependence shall be within ±15% over the range 0.01 MeV to 1.25 MeV (more than one detector permissible).

(4) Response shall be minimized and known for beta and neutron radiations as a function of their respective intensities and energies and a statement of the response furnished with the instrument.

(5) The operating range shall be 0.5 mR/h to at least 5000 mR/h.

5.2.3 Neutron survey instruments shall meet the following performance criteria:

(1) The response for neutron energies in the range from thermal to 10 MeV shall approximate the dose equivalents given in Table 1 for those instruments designed for dose equivalent rate measurements.

(2) The angular dependence should be within ±15% in a 2π steradian frontal direction for ^{252}Cf energy neutrons or equivalent.

(3) The response to photon radiations shall be minimized, known, and a statement of the response furnished with the instrument.

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TABLE 1
Neutron Fluence Dose Equivalents*

Neutron Energy (MeV)	Neutrons per Square Centimeter per Rem	Rem per Neutron per Square Centimeter
Thermal	$980 \cdot 10^6$	$1.0 \cdot 10^{-9}$
0.0001	$840 \cdot 10^6$	$1.2 \cdot 10^{-9}$
0.001	$980 \cdot 10$	$1.0 \cdot 10^{-9}$
0.01	$1000 \cdot 10^6$	$1.0 \cdot 10^{-9}$
0.1	$170 \cdot 10^6$	$6.1 \cdot 10^{-9}$
0.5	$39 \cdot 10^6$	$26.0 \cdot 10^{-9}$
1.0	$27 \cdot 10^6$	$37.0 \cdot 10^{-9}$
2.5	$29 \cdot 10^6$	$34.0 \cdot 10^{-9}$
5.0	$23 \cdot 10^6$	$43.0 \cdot 10^{-9}$
7.5	$24 \cdot 10^6$	$42.0 \cdot 10^{-9}$
10.0	$24 \cdot 10^6$	$42.0 \cdot 10^{-9}$
20.0	$16 \cdot 10^6$	$63.0 \cdot 10^{-9}$

*See references [5] and [6].

(4) The operating range shall be 0.2 mrem/h to at least 2000 mrem/h.

5.3 Fixed Monitoring Instruments

5.3.1 Airborne contamination monitors are normally of the continuous type commonly referred to as continuous air monitors (CAMs). The following criteria apply to those instruments. More information on air monitoring is contained in ANSI N13.10-1974 [4].

(1) The minimum detection level shall be 1 MPC of ^{239}Pu in 8 h (8 MPC hours) in the presence of nominal amounts of naturally occurring alpha emitters such as radon and thoron and their daughters. (This requirement is applicable to MPC values as of the date of this standard.)

(2) The operating range of the instrument shall be at least 10^2 minimum detectable levels.

(3) The instrument error shall not exceed ±20% of reading over the upper 80% of its operating range where the error is defined as:

$$\% \text{ errors} = \frac{Rr - Rt}{Rt} \cdot 100\%$$

where:

Rr = indicated quantity
Rt = true quantity

For this determination, the indicated quantity Rr shall be taken from the most accurate readout format; for example, recorder output or analog-to-digital converter. The usual instrument panel meters may significantly contribute to the error (particularly in logarithmic devices) but these are rarely used as the primary quantitative readout.

(4) The reproducibility of the system for any given measurement over its stated range should be within ±10% at the 95% confidence level for a midscale or mid-decade reading.

(5) The response time of the electronic system should not be greater than that required to maintain background readings within the required accuracy.

(6) The instrument shall be capable of continuous operation, within the required accuracy, when tested in relative humidities of 40 to 95%.

(7) The instrument should be capable of continuous operation under ambient pressures expected with less than 5% change in calibration.

(8) The instrument shall be capable of operating with less than 5% change in calibration over the ambient temperature range expected.

(9) The instrument shall be equipped with an alarm trip which can be set at any point over the stated range and should be capable of adjustment and reset without removing the instrument from service. The alarm shall be both audible and visible at the instrument and provisions shall be made for the signal to be transmitted to another location.

(10) The instrument shall be equipped with an alarm device which provides appropriate notification at any time if the system is incapable of monitoring radiation, or if a failure occurs in any component or circuit which would affect the accuracy of the readout. A latching

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contact shall be provided to indicate loss of signal, detector operating voltage, or circuit power.

(11) Voltage and frequency variations of ±15% within the design values shall result in reading variations of no greater than ±5% at the minimum detectable level.

(12) Power line noise suppression systems shall be provided to minimize erroneous instrument readings and trips.

(13) Radio frequency microwave signals $\leq 10\ \mu W/cm^2$ shall result in reading variations of no greater than ±5% at the minimum detectable level.

(14) For those monitors with emergency power sources, either battery or other than normal ac power, the monitor should be able to operate in the emergency power mode for at least 18 h in a nonalarm condition and for at least 2 h in an alarm condition.

(15) Air flow rate shall be indicated and adjustable. Capabilities for maintaining a constant flow rate should be considered. Air flow rates should be ≥ 0.5 cfm.

(16) Air sample lines between air inlet and filter media should be eliminated where possible and where not possible shall be designed to meet sampling criteria contained in ANSI N13.1-1969 [7].

(17) A thorough primary calibration [8] of the entire system shall be performed at least once using a radionuclide of known concentration. The radionuclide shall have energies and intensities such as to permit calibrating the range of energy and rate capabilities intended for the system. Traceability to a national standard shall be maintained. The calibration shall be related to a secondary source or method which will be used for periodic recalibration. The source-to-detector geometry shall be maintained identical to that established during the primary calibration. The surface dimensions of the secondary source shall be the same size as the collecting media area. Flow rate measuring devices associated with the system shall be calibrated to determine actual flow rate at the conditions of temperature and pressure under which the system will be operated. These flow rate devices shall be periodically recalibrated.

5.3.2 Surface contamination monitors consist primarily of hand or shoe counters and instruments (or probes), or both, with sufficient flexibility to survey pieces of equipment, including exterior clothing. The following performance criteria apply to these instruments:

(1) The instrument shall have an audible alarm, the frequency which is proportional to the count rate or a pre-selectable trip setting and upon reaching that level shall activate an audible or visible alarm, or both.

(2) The instrument shall be provided with a check source furnished by the user.

(3) Requirements stated for portable survey instruments in 5.1.1, 5.1.3, and 5.2.1 shall apply.

(4) Fixed instruments should be ac powered and provided with an emergency power source.

5.3.3 Photon and neutron area monitors consist primarily of instrumentation used for active monitoring of photon and neutron radiation intensities in areas where significant quantities of plutonium are stored or handled, or both. The following performance criteria apply to these instruments:

(1) The instrument shall have a pre-selectable trip setting with audible annunciators and shall provide electronic signals for remote alarms if used as an alarming device.

(2) The instrument shall be equipped with a visual meter or a digital readout.

(3) Requirements stated for portable survey instruments in paragraphs 5.1.1, 5.1.3, 5.2.2, and 5.2.3 shall apply.

(4) All neutron and photon area monitoring instruments should be ac powered and provided with an emergency power source.

5.3.4 Criticality alarm systems, any and all, shall comply with ANSI N16.2-1969, [17].

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Appendix

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Appendix A

Plutonium Radiation Parameters

A1. Isotopic Compositions

There are no stable isotopes of plutonium and, since the bulk of the plutonium produced is by neutron capture in ^{238}U, there are relatively small amounts of isotopically pure plutonium available. Therefore, the plutonium most commonly found in the nuclear industry consists of a mixture of isotopes ranging from ^{236}Pu to ^{242}Pu in varying percentages. The number and amount of each isotope is a complex function of the original fuel and reactor irradiation history. An indication of the ranges to be expected can be found in Table A1.

The isotopic composition of plutonium produced in light water reactors (LWRs) is a complex function of initial fuel, the reactor and the fuels' irradiation history. Data in Table A1 summarize the computed average isotopic compositions as a function of burnup for the two types of LWRs, that is, pressurized and boiling water reactors. No attempt is made to detail any specific isotopic composition but rather to give the reader of this standard some knowledge of the ranges of isotopic compositions to expect.

It is common practice to broadly classify plutonium as either *low exposure* or *high exposure* depending on the burnup of the initial fuel from which the plutonium was recovered. This standard suggests that any plutonium which contains eighty (80) or less weight percent of ^{239}Pu be classified as *high exposure* plutonium.

A2. Decay Radiations

The radiations from the radioactive decay of plutonium consist of alpha, beta, X-ray, gamma and neutron radiations in various amounts and energies.

Tables A2 and A3 summarize the important radiations and their yield from plutonium and significant daughters. Neutron yields for selected plutonium compounds are also given in Table A3.

TABLE A1*
Typical Isotopic Composition for Various Plutonium Types
(weight percent)

Type	10^3 Burnup MWD/T	^{236}Pu	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Production	—	—	—	94.5	5.0	0.5	—
Pressurized Water Reactor (PWR)	14.5 ± 1	$5.1 \cdot 10^{-6}$	0.42	67.0	21.7	9.2	2.1
	24.0 ± 2	$1.2 \cdot 10^{-5}$	1.0	58.5	23.9	11.9	4.4
	29.5 ± 1.5	$1.7 \cdot 10^{-5}$	1.4	56.5	23.5	13.0	5.2
	32.5 ± 0.5	$2.1 \cdot 10^{-5}$	1.7	55.5	24.3	13.4	5.7
Boiling Water Reactor (BWR)	19.0 ± 1.5	$8.0 \cdot 10^{-6}$	0.9	61.7	22.4	11.3	3.4
	23.0 ± 0.5	$1.1 \cdot 10^{-5}$	1.3	56.9	23.8	12.7	5.3
	27.0 ± 1.0	$1.4 \cdot 10^{-5}$	1.7	52.4	25.0	13.7	6.6
	28.0 ± 1.0	$1.5 \cdot 10^{-5}$	1.8	54.2	23.8	13.5	6.4
^{238}Pu Fuel	—	$1.0 \cdot 10^{-5}$	80.0	16.3	3.0	0.6	0.1

*See Section 6, [9], [10], [11], [12], [13].

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TABLE A2
Radioactive Decay Properties of Selected Plutonium Isotopes and Daughters Excluding Spontaneous Fission**

Isotope	Half-Life	Mode of Decay: Particle	Energy-MeV	Yield %	X-Ray: Energy-MeV	Yield %	Gamma Ray: Energy-MeV	Yield %
^{236}Pu	2.85 y*	α	5.77	69	Ls 0.011- 0.021	10†	0.047	$3.1\cdot10^{-2}$
		α	5.72	31			0.110	$1.2\cdot10^{-2}$
							0.165	$6.6\cdot10^{-4}$
							0.473-0.645‡	$5.2\cdot10^{-4}$
^{238}Pu	87.7 y	α	5.49	72	Ls 0.011-21.4	10.5	0.0435	$3.9\cdot10^{-2}$
		α	5.45	28			0.0999	$7.4\cdot10^{-3}$
		α	5.35	0.13			0.1528	$1.0\cdot10^{-3}$
							0.201-1.085	$3.8\cdot10^{-5}$
^{239}Pu	$2.44\cdot10^{4}$ y	α	5.147	73.3	Ls 0.0116- 0.0215	4.8	0.0387	$5.9\cdot10^{-3}$
		α	5.134	15.1			0.0516	$2.1\cdot10^{-2}$
		α	5.095	11.5			0.129	$6.2\cdot10^{-3}$
							0.375	$1.58\cdot10^{-3}$
							0.414	$1.51\cdot10^{-3}$
							0.142-1.057	$4.93\cdot10^{-3}$
^{240}Pu	$6.6\cdot10^{3}$ y	α	5.159	75	Ls 0.0115- 0.0215	10.8	0.0452	$4.5\cdot10^{-2}$
		α	5.115	25			0.104	$7.0\cdot10^{-3}$
							0.160	$4.2\cdot10^{-4}$
^{241}Pu	15 y	β	0.0222	99.99+			0.0442	$4.5\cdot10^{-6}$
		α	4.896	83% of $2.3\cdot10^{-3}$%			0.0448	$1.1\cdot10^{-6}$
		α	4.853	12% of $2.3\cdot10^{-3}$%			0.0563	$3.7\cdot10^{-6}$
		α	4.797-5.055	5% of $2.3\cdot10^{-3}$%			0.077	$2.41\cdot10^{-5}$
							0.1037	$1.04\cdot10^{-4}$
							0.121	$8.9\cdot10^{-7}$
							0.148	$1.9\cdot10^{-4}$
							0.160	$6.45\cdot10^{-6}$
^{242}Pu	$3.79\cdot10^{5}$ y	α	4.903	76	Ls 0.0116- 0.0215	4.1	0.0447	$5\cdot10^{-2}$
		α	4.863	24				
^{241}Am	458 y	α	5.486	86	Ls 0.0119-22.2	37.6	0.0434	$9.1\cdot10^{-2}$
		α	5.443	12.7				
		α	5.389	1.3			0.0595	35.9
							0.0699	$2\cdot10^{-3}$
							0.099	$2\cdot10^{-2}$
							0.103	$1.95\cdot10^{-2}$
							0.123	$1\cdot10^{-3}$
							0.125	$3.95\cdot10^{-3}$
							0.146	$4.6\cdot10^{-4}$
							0.150	$7.2\cdot10^{-5}$
							0.159-0.2927	$1.17\cdot10^{-3}$
							0.301-0.4863	$1.39\cdot10^{-3}$
							0.514-0.863	$7.2\cdot10^{-4}$
^{237}U	6.75 d	β	0.248	96	Ls 0.0119- 0.0208	62.9	0.0264	2.4
							0.0332	$1.9\cdot10^{-2}$
							0.0434	$7.4\cdot10^{-2}$
							0.051	0.22
							0.0595	36
							0.208	23.3
							0.0648-0.371	6.3

*y = years; d = days
†Total for all X-rays
‡Gamma rays of many energies are in these groups. Yield is for the gammas included in the range exclusive of those listed separately.
**See Section 6, [14], [15], [16].

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A3. Theoretical Dose Rates

Plutonium is extremely radiotoxic and, therefore, every precaution is taken to preclude any direct exposure of personnel to plutonium or its aerosols. Physical contact with plutonium is done routinely but always with the benefit of some intervening material such as surgeon's gloves or glove box gloves, etc. This practice accomplishes at least two things: (1) It reduces the amounts and types of direct radiation exposure and (2) It normally maintains containment since gloves are an integral part of the containment system.

Often an estimate is needed of the intensity and resulting exposure rate to be expected from a particular isotopic composition and as a function of time since chemical separation or purification. The radiation intensity is continually changing, primarily increasing at least for time periods of interest here. The change is due to the decay of ^{241}Pu into its daughters ^{237}U and ^{241}Am. The net ingrowth or buildup is expressed by the following equation:

$$\frac{A_x}{A_{Pu}} = \frac{f_x \lambda_x}{\lambda_x - \lambda_{Pu}} 1 - e^{-(\lambda_x - \lambda_{Pu})t}$$

where

$\frac{A_x}{A_{Pu}}$ = the activity ratio,
f_x = the fraction of decays resulting in x,
λ_i = the decay constant of the i^{th} radioisotope, and
t = time since separation in the same units as the half lives.

Solving this equation for ^{237}U, at about 50 days (t=50 days), the exponent approaches zero and equilibrium is established. For the ^{241}Am daughter, equilibrium is not established for long times, but grows in at an almost linear rate for several years after chemical separation. These two properties are important because they can be utilized to derive an equation which can be used to calculate *surface* dose rates associated with plutonium of any isotopic composition and for any time since chemical separation between about 35 d and 12 yr. *Surface* is by definition, at least a few hundreths of a centimeter away due to the intervening material, be it surgeon's gloves, plastic bags or some other thin material which is close to tissue in density and atomic number. The following equations have been derived and verified experimentally for the

TABLE A3
Neutron Yields from Selected Plutonium Isotopes and Compounds*

Isotope	Spontaneous Fission Half-Life	v n/Fission	Yield n/gm-s	(α,n) Reactor Rate n/gm-s Isotope
^{236}Pu	$3.5 \cdot 10^9$ y	2.3	$3.7 \cdot 10^4$	
^{238}Pu	$4.9 \cdot 10^{10}$ y	2.33	$2.62 \cdot 10^3$	
$^{238}PuF_4$				$2.1 \cdot 10^6$
$^{238}PuO_2$				$1.4 \cdot 10^4$
^{239}Pu	$5.5 \cdot 10^{15}$ y	3.0	$3 \cdot 10^{-2}$	
$^{239}PuF_4$				$4.3 \cdot 10^3$
$^{239}PuO_2$				$4.5 \cdot 10^1$
^{240}Pu	$1.22 \cdot 10^{11}$ y	2.25	$1.02 \cdot 10^3$	
$^{240}PuF_4$				$1.6 \cdot 10^4$
$^{240}PuO_2$				$1.7 \cdot 10^2$
^{242}Pu	$7.1 \cdot 10^{10}$ y	2.18	$1.7 \cdot 10^3$	
$^{242}PuF_4$				$1.7 \cdot 10^2$
$^{242}PuO_2$				2.7
^{244}Pu	$2.5 \cdot 10^{10}$ y	2.3†	$5.1 \cdot 10^3$	
$^{241}AmO_2$				$2.64 \cdot 10^3$

*See Section 6, [19].
†Estimated

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gamma, X-ray portion of the total exposure rate for a wide isotopic range and time since separation and for relatively thick sources. Because of density difference, thick sources are defined as $\geq$0.127 cm for plutonium metal and $\geq$0.9 cm of PuO_2. The equation [9] for plutonium is:

$$Ds(\text{rd/h}) = 171\, f_{238} + 0.51\, f_{239} + 2.4\, f_{240} + 8.7\, f_{241} + 0.15\, f_{242} + [0.074\, f_{241}]\, t$$

where

Ds = *surface* dose rate
f_i = weight fraction of the i^{th} isotope
t = time since chemical separation in days, $\geq$35 days.

The value of Ds from the above equation becomes the basis for evaluating the decrease in surface dose rate when plutonium oxide is blended with uranium oxide in a mixed oxide fuel. The mixed oxide (MO_2) surface dose rate equation is:

$$Dsm(\text{rd/h}) = Ds[0.13(1\text{-}x)^{0.75} + x^{0.75}] + 0.1\ \text{rd/h}$$

where

Dsm = surface dose rate of MO_2
Ds = surface dose rate of PuO_2
x = weight fraction of PuO_2 in MO_2

The use of the surface dose rate equations can be illustrated assuming an isotopic composition equal to that given in Table A1, pressurized water reactor (PWR) at 29.5 MWD/T, 240 d since chemical separation and mixed with UO_2 at 3 weight percent Pu.

$$\begin{aligned} Ds &= (171 \cdot 0.014 + 0.51 \cdot 0.565 + 2.4 \cdot 0.235 + 8.7 \cdot 0.13 + 0.15 \cdot 0.052) \\ &\quad + [(0.074 \cdot 0.13)240]\ \text{rd/h} \\ &= (2.4 + 0.29 + 0.56 + 1.13 + 0.01 + 2.31)\ \text{rd/h} \\ &= 6.7\ \text{rd/h} \end{aligned}$$

$$\begin{aligned} Dsm &= 6.7\,[0.13\,(1 - 0.03)^{0.75} + 0.03^{0.75}] + 0.1\ \text{rd/h} \\ &= 6.7\,[0.13\,(0.97^{0.75} + 0.03^{0.75}] + 0.1\ \text{rd/h} \\ &= 6.7\,[0.13 + 0.07] + 0.1\ \text{rd/h} \\ &= 1.44\ \text{rd/h} \end{aligned}$$

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