DEFENSE THREAT REDUCTION AGENCY

NUCLEAR TEST PERSONNEL REVIEW PROGRAM

RADIATION DOSE ASSESSMENT

STANDARD METHOD

ED05 – Lens of the Eye Dose

Revision 2.0

Cleared for Release

Key to SOP ID Codes

RA (Radiation Assessment - SOP)
ED (External Dose - Standard Methods)
ID (Internal Dose - Standard Methods)
UA (Uncertainty Analysis - Standard Methods)

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Standard Method

ED05 – Lens of the Eye Dose

1. Purpose/Summary

Standard Method (SM) ED05, *Lens of the Eye Dose*, provides general technical methods for assessing dose to the lens of the human eye from surface deposited fallout, activated sources, and dermal contamination to individuals in the Nuclear Test Personnel Review (NTPR) Program according to the procedures specified in SOP RA01.

2. Scope

This standard method provides technical guidance for reconstructing dose to the lens of the eye due to beta and gamma ionizing radiation as a result of source exposure. This standard method should not be used to determine skin doses due to alpha radiation, internally deposited radioactive material exposures, or as the sole method for determining external radiation exposures (including skin contamination). This standard method is used in conjunction with SMs ED03, *Skin Dose from External Sources*, and ED04, *Skin Dose from Dermal Contamination*, for assessing whole body external radiation exposures in accordance with the requirements of Title 32, Code of Federal Regulations, Part 218 "*Guidance for the Determination and Reporting of Nuclear Radiation Dose for DoD Participants in the Atmospheric Nuclear Test Program"* (DoD, 2020).

3. Responsibilities

Qualified radiation dose analysis staff members use these methods and associated tools for assessing the radiation doses for exposed individuals. If situations arise where these methods and techniques are inadequate to address a specific exposure scenario, it is the responsibility of the analyst encountering this deficiency to bring it to the attention of the RDA Manager so that the methodology can be extended as required to provide adequate estimates of lens of the eye doses. It is the responsibility of the analyst executing and implementing this extension to document such extension in a revision to this standard method.

4. Definitions

Individual: Any person who participated in the nuclear weapons testing program as a member of the US armed forces.

Infinite Plane Gamma Source: Fallout deposited over a large surface is considered to be an infinite geometric plane with uniform, isotropic emission from each point source in the plane (Barss and Weitz, 2006). Such a surface is generally represented by land (Pacific Islands and the Nevada Test Site [NTS]) where the gamma radiation can originate up to 200 meters (m) or more from an individual standing on the ground.

Finite Plane Gamma Source: Fallout deposited over a very small area with respect to the infinite source with localized contamination and isotropic emission from each point source. Shrinking a finite gamma source down to its lowest diameter constitutes point source geometry.

5. Method Description

5.1 Introduction

Individuals present during the nuclear weapons testing at the Pacific Proving Ground (PPG) or the NTS were potentially exposed to initial gamma and neutron emissions from a detonation, mixed fission products and actinides in fallout, and neutron activation products in the soil and surrounding environment. The initial gamma emissions for the nuclear detonation, along with mixed fission products in fallout and activation products, present an external gamma exposure source to the lens of the eye.

In close proximity to the body, beta radiation can have sufficient energy to penetrate to the lens of the eye; thus it can also be considered an external radiation source contributing to lens dose along with gamma radiation (Turner, 1995).

Film badges were worn by many individuals, or groups of individuals, during weapon testing activities. These monitoring devices measured the amount of gamma radiation individuals received during testing activities. If a specific individual did not wear a film badge, it is possible to reconstruct the individual's exposure, based upon film badges worn by other individuals in the nearby vicinity or using radiological intensity data. Utilizing film badge data or gamma dose reconstruction, it is also possible to estimate the dose the individual received to the lens of the eye due to beta radiation from the surrounding radiological environment.

5.2 Gamma Dose to Lens of Eye from Fallout

Film badge readings or reconstructed gamma doses form the basis to estimate the whole body gamma dose.

Gamma radiation has sufficient energy to penetrate the lens tissue of the eye as well as the epidermal skin layer, along with the body organs and skeleton structure. For the purposes of dose reconstruction, dose to the lens due to gamma radiation is assumed to be the same as the whole body external dose based on a film badge or reconstruction, not taking into consideration attenuation characteristics of distance, geometry, and tissue depth. This method establishes conservative worst-case gamma doses to the lens of the eye, which are subsequently used to estimate a beta dose from a beta-to-gamma dose ratio. The whole body dose is based on the film badge reading or on a film badge equivalent dose calculated by reconstruction according to SM ED02 - *Whole Body External Dose - Reconstruction*, and must be characterized first in order to use the following standard methods.

5.3 Beta Dose to Lens of Eye from Fallout

Beta dose to the lens from external sources is accrued simultaneously with the gamma dose from mixed fission products and actinides in fallout or neutron induced radionuclides (activated sources). As a result, the beta dose is proportional to the gamma dose, and its relative magnitude can be expressed by a beta-to-gamma dose ratio. This beta-to-gamma dose ratio is dependent on the spectrum of the emitted radiation and on the geometrical relationship between an individual and the source (e.g., distance from or height above the source, or finite or infinite plane geometry). Gamma and beta energy spectra are interdependent functions of time, and consequently, the beta-to-gamma dose ratio depends on time after a detonation (Barss and Weitz, 2006).

Due to beta particle range and attenuation characteristics, beta dose assessments depend more critically than gamma dose assessments on geometry and the shielding material between the radioactive source and the individual. Thus, the nature of specific jobs or task-related activities and their associated protective measures must be considered when reconstructing beta dose to the lens (Barss and Weitz, 2006).

Beta doses to the eye are evaluated at the lens of the eye. The depth for the evaluation is 3 mm (300 mg cm^{-2}) from the anterior surface of the eye where the lenticular tissue at risk for posterior subcapsular cataract development is located. This depth is consistent with ICRP (2002) as the reference density thickness.

Beta doses from external origin generally involve three exposure pathways based on infinite, finite, and point source geometries. Fallout deposited over a large surface (such as a residence island in the Pacific) is considered to be an infinite plane with uniform, contamination and isotropic emission from each point source in the plane (Barss and Weitz, 2006). Fallout deposited over a small area or surface is considered to be a finite source with localized contamination and isotropic emission (Weitz, 2011). Finite radiation sources include the contaminated topside of a ship, contaminated equipment, and material such as aircraft engines. Fallout deposited as a “hot-spot” is considered to be point-source geometry.

Beta doses to the lens of the eye do not consider the attenuation effects of the eyelid or glasses.

5.3.1 Infinite Plane Source

For a person exposed to an infinite-sized fallout-contaminated area while wearing a film badge or from a reconstructed gamma dose, the dose to the lens can be estimated using the same methods and general equations number 1, 3, 4, and 5 as specified in Section 5.2.1 of ED03, replacing the beta-to-gamma ratios for skin with the beta-to-gamma ratios for the lens of the eye as specified in Table 1 and Table 2 below and after adjustment for the height of the head from a ground surface based on the individual’s height while standing or sitting (Stiver, 2006).

Table 1. Lens Beta-to-Gamma Dose Ratios as Function of Time and Height (cm) at PPG

Time	[days]	at H = 1 cm	at H = 10 cm	at H = 20 cm	at H = 40 cm	at H = 60 cm	at H = 80 cm	at H = 100 cm	at H = 120 cm	at H = 160 cm	at H = 200 cm
0.5 hour	0.0208	3.61	3.45	3.28	2.97	2.69	2.44	2.22	2.02	1.67	1.39
1 hour	0.0417	2.87	2.74	2.60	2.33	2.09	1.88	1.69	1.53	1.24	1.01
2 hours	0.0833	2.64	2.51	2.38	2.12	1.90	1.70	1.52	1.37	1.10	0.89
4 hours	0.1667	3.21	3.05	2.89	2.59	2.33	2.09	1.88	1.69	1.38	1.13
6 hours	0.25	3.96	3.77	3.58	3.22	2.89	2.61	2.35	2.13	1.74	1.43
12 hours	0.5	4.23	4.02	3.80	3.40	3.04	2.73	2.45	2.21	1.79	1.46
1 day	1	2.56	2.40	2.24	1.96	1.72	1.51	1.33	1.17	0.91	0.71
2 days	2	1.30	1.20	1.10	0.92	0.78	0.66	0.57	0.48	0.36	0.26
3 days	3	0.86	0.78	0.71	0.57	0.47	0.39	0.32	0.27	0.19	0.13
1 week	7	0.53	0.48	0.43	0.34	0.27	0.22	0.18	0.15	0.10	0.07
2 weeks	14	0.61	0.56	0.50	0.40	0.32	0.26	0.22	0.18	0.12	0.09
1 month	30	0.93	0.85	0.77	0.63	0.52	0.43	0.36	0.30	0.22	0.16
2 months	60	1.59	1.47	1.35	1.14	0.96	0.82	0.70	0.60	0.45	0.34
4 months	120	2.44	2.29	2.13	1.85	1.61	1.40	1.23	1.07	0.83	0.65
6 months	180	3.32	3.14	2.95	2.60	2.30	2.04	1.80	1.60	1.27	1.00
9 months	270	5.74	5.47	5.18	4.64	4.15	3.72	3.33	2.99	2.40	1.92
1 year	365	10.42	9.96	9.46	8.52	7.68	6.91	6.22	5.59	4.51	3.62
2 years	730	36.55	34.97	33.27	30.08	27.17	24.52	22.10	19.90	16.07	12.90

Table 2. Lens Beta-to-Gamma Dose Ratios as Function of Time and Height (cm) at NTS

Time	[days]	at H = 1 cm	at H = 10 cm	at H = 20 cm	at H = 40 cm	at H = 60 cm	at H = 80 cm	at H = 100 cm	at H = 120 cm	at H = 160 cm	at H = 200 cm
0.5 hour	0.0208	3.56	3.41	3.26	2.98	2.72	2.49	2.28	2.09	1.76	1.48
1 hour	0.0417	2.84	2.72	2.59	2.34	2.13	1.93	1.75	1.59	1.32	1.09
2 hours	0.0833	2.61	2.49	2.37	2.14	1.93	1.74	1.58	1.43	1.17	0.96
4 hours	0.1667	3.18	3.04	2.89	2.62	2.37	2.15	1.95	1.77	1.47	1.22
6 hours	0.25	3.91	3.74	3.56	3.23	2.94	2.67	2.43	2.21	1.84	1.54
12 hours	0.5	4.16	3.97	3.77	3.40	3.08	2.79	2.53	2.29	1.89	1.57
1 day	1	2.51	2.38	2.23	1.97	1.75	1.55	1.38	1.23	0.98	0.78
2 days	2	1.28	1.19	1.10	0.94	0.80	0.69	0.59	0.52	0.39	0.29
3 days	3	0.85	0.78	0.71	0.59	0.49	0.41	0.34	0.29	0.21	0.15
1 week	7	0.52	0.47	0.43	0.35	0.28	0.23	0.19	0.16	0.11	0.08
2 weeks	14	0.60	0.55	0.50	0.41	0.34	0.28	0.23	0.20	0.14	0.10
1 month	30	0.92	0.85	0.77	0.65	0.54	0.46	0.39	0.33	0.24	0.18
2 months	60	1.57	1.46	1.35	1.15	0.99	0.85	0.74	0.64	0.48	0.37
4 months	120	2.40	2.26	2.12	1.86	1.64	1.44	1.27	1.13	0.89	0.71
6 months	180	3.26	3.10	2.93	2.61	2.33	2.09	1.87	1.67	1.35	1.09
9 months	270	5.63	5.38	5.12	4.63	4.19	3.79	3.43	3.10	2.53	2.07
1 year	365	10.25	9.83	9.38	8.53	7.76	7.05	6.40	5.81	4.78	3.92
2 years	730	35.95	34.53	33.00	30.10	27.44	24.99	22.74	20.67	17.03	13.97

The computational method used to calculate the above ratios was the same as that used to calculate the skin beta-to-gamma ratios (SM ED03) with the skin being replaced by a 3 mm over-layer and a 1 cm backing layer of water (Barss and Weitz, 2006).

5.3.2 Finite Plane Source

Similar to the finite plane source dose ratios for skin, calculations were performed to derive finite source beta-to-gamma dose ratios for the lens. Examples of some scenarios involving eye exposures to finite-sized sources of beta and gamma radiation include decontaminating an aircraft engine and other surfaces, operating a small shuttle boat, performing post-decontamination maintenance activities, and performing maintenance on evaporators in the engine room of a contaminated ship.

The results shown in this standard method are analogous in concept to those provided for the basal skin layer. The computational method employing the radiation transport code ITS CYLTRAN (Halbleib et al., 1992) is identical to that described in (Barss and Weitz, 2006), except that the skin model is replaced with an eye model consisting of a 3-millimeter (mm) over-layer, a 1-micrometer (μm) sensitive layer (for the lens), and a 1-centimeter (cm) backing layer, all composed of standard-density water. The time-dependent beta and gamma fallout spectral data are taken from (Finn et al., 1979). The beta-to-gamma dose ratios presented in this section apply to an individual looking directly at the radiation source, i.e., no shielding factors are included. It is also assumed that the beta dose in the numerator of the ratio and gamma dose in the denominator were accrued at the same distance from the source, as would generally be the case if the gamma dose is a film badge or film badge equivalent dose (i.e., a reconstruction).

Beta and gamma dose to the lens of the eye based on finite geometry is calculated in an identical manner as for external skin dose based on finite geometry (as specified in SM ED03), replacing the beta-to-gamma finite dose ratios for skin with those specified for the lens of the eye.

The eye lens beta-to-gamma dose ratios are presented in this section as functions of source radius, source distance (H), substrate material, and time after detonation (Weitz, 2012).

Typical radii for aircraft decontamination range from 3 (F-84) to 5 m (B-29) based on size of aircraft.

Table 3 provides an index for the finite applications and associated beta-to-gamma dose ratios listed in Tables 4 through 14 for the specified substrate (Aluminum or Iron), distance from source (H), and job activity.

NOTE: The only difference between PPG and NTS beta-to-gamma dose ratio calculations is an air density of 1.15 and 1.05 mg cm^{-3}, respectively (Barss and Weitz, 2006). The beta-to-gamma dose ratio for the lens is slightly greater at NTS due to the less dense air; see Table 6 and Table 7, ratios for 4 hours.

Table 3. Index to Tables of Typical Finite Applications and Associated Beta-to-Gamma Lens Dose Ratios

Substrate	**Distance (m)**	**Activity**	**Location**
Al	0.1	Aircraft inspection & maintenance (PPG)	Table 4
Al	0.5	Decon equipment (NTS)	Table 5
Al	1.0	Decon aircraft (NTS)	Table 6
Al	1.0	Decon aircraft (PPG)	Table 7
Al	2.0	Decon aircraft (NTS)	Table 8
Al	3.66 (12 ft)	Decon aircraft with high pressure hose (PPG)	Table 9
Fe	0.3 (1 ft)	Hand scrub decon aboard ship (PPG)	Table 10
Fe	0.5	Decon (NTS)	Table 11
Fe	1.0	Decon (NTS)	Table 12
Fe	1.0	Decon (PPG)	Table 13
Fe	2.0	Decon (NTS)	Table 14

Table 4. Al at Distance H = 0.1 m (PPG)

Source	Time after Detonation:				
Radius (m)	1 hour	4 hours	1 day	1 week	6 months
0.10	18.3	21.0	14.6	3.9	19.2
0.25	13.2	15.2	10.3	2.5	13.4
0.50	10.3	11.9	7.9	1.8	10.3
1	8.3	9.6	6.4	1.4	8.3
2	6.9	8.0	5.3	1.2	6.9
3	6.3	7.3	4.8	1.1	6.3
4	5.9	6.8	4.5	1.0	5.9
5	5.6	6.5	4.3	1.0	5.7
7	5.2	6.0	4.0	0.89	5.3
10	4.9	5.6	3.8	0.83	5.0
15	4.5	5.2	3.6	0.78	4.7
20	4.3	5.0	3.4	0.74	4.5
50	3.8	4.4	3.0	0.66	4.0
100	3.5	4.1	2.8	0.61	3.7
200	3.3	3.8	2.7	0.58	3.5
500	3.2	3.7	2.6	0.56	3.4

Table 5. Al at Distance H = 0.5 m (NTS)

Source	Time after Detonation:			
Radius (m)	2 hours	4 hours	6 hours	12 hours
0.10	17.7	21.2	26.6	28.8
0.25	17.3	20.5	25.4	26.8
0.50	15.0	18.1	22.4	23.5
1	11.6	14.1	17.4	18.3
2	8.6	10.6	13.0	13.4
3	7.3	8.9	11.0	11.3
4	6.5	8.0	9.8	10.1
5	6.0	7.3	9.0	9.3
7	5.3	6.5	8.1	8.2
10	4.8	5.9	7.2	7.4
15	4.3	5.2	6.5	6.6
20	4.0	4.9	6.0	6.2
50	3.3	4.1	5.0	5.1
100	3.0	3.7	4.5	4.6
200	2.8	3.4	4.2	4.3
500	2.6	3.3	4.0	4.1

Table 6. Al at Distance H = 1 m (NTS)

Source Radius (m)	Time after Detonation: 2 hours	4 hours	6 hours	12 hours
0.10	16.2	21.0	25.6	24.3
0.25	16.8	19.2	25.3	26.3
0.50	15.9	19.2	23.7	25.2
1	13.5	16.7	20.7	21.4
2	10.0	12.3	15.4	15.8
3	8.1	10.0	12.5	12.7
4	7.0	8.6	10.7	10.9
5	6.2	7.7	9.6	9.8
7	5.3	6.6	8.2	8.3
10	4.5	5.7	7.0	7.1
15	3.9	4.9	6.1	6.2
20	3.6	4.5	5.5	5.6
50	2.8	3.6	4.4	4.5
100	2.5	3.1	3.9	4.0
200	2.3	2.9	3.6	3.7
500	2.2	2.7	3.4	3.5

Table 7. Al at Distance H = 1 m (PPG)

Source Radius (m)	Time after Detonation: 1 hour	4 hours	1 day	1 week	6 months
0.10	18.0	20.9	17.2	3.1	25.9
0.25	18.3	20.0	16.6	3.1	21.3
0.50	17.3	18.8	15.3	2.8	20.0
1	15.0	16.1	12.5	2.1	17.2
2	10.9	11.9	8.7	1.3	11.9
3	8.7	9.7	6.8	1.0	9.3
4	7.5	8.3	5.7	0.81	7.8
5	6.6	7.4	5.1	0.71	6.9
7	5.6	6.3	4.3	0.60	5.8
10	4.8	5.4	3.7	0.51	5.0
15	4.2	4.7	3.2	0.44	4.3
20	3.8	4.3	2.9	0.40	3.9
50	3.0	3.4	2.3	0.32	3.1
100	2.7	3.0	2.1	0.28	2.7
200	2.5	2.8	1.9	0.26	2.5
500	2.4	2.6	1.8	0.25	2.4

Table 8. Al at Distance H = 2.0 m (NTS)

Source	**Time after Detonation:**			
Radius (m)	**2 hours**	**4 hours**	**6 hours**	**12 hours**
0.10	12.5	14.9	22.7	28.0
0.25	13.1	17.4	19.8	21.7
0.50	13.1	16.7	20.3	22.2
1	12.5	15.2	18.7	20.8
2	10.1	12.7	15.4	16.6
3	8.2	10.2	12.6	13.4
4	6.8	8.6	10.7	11.2
5	5.8	7.5	9.3	9.6
7	4.7	6.1	7.5	7.7
10	3.8	4.9	6.1	6.2
15	3.1	4.0	5.0	5.0
20	2.7	3.5	4.4	4.4
50	2.0	2.6	3.2	3.3
100	1.7	2.2	2.8	2.8
200	1.6	2.0	2.5	2.6
500	1.5	1.9	2.4	2.4

Table 9. Al at Distance H = 2.0 m (NTS)

Source	**Time after Detonation:**		
Radius (m)	**6 hours**	**12 hours**	**1 day**
0.5	9.2	11.0	5.0
1	9.8	10.4	5.2
2	8.9	8.9	4.4
3	7.7	7.9	3.6
4	6.6	6.6	2.9
5	5.8	5.7	2.5
7	4.5	4.4	1.8
10	3.4	3.3	1.3
15	2.6	2.5	1.0
20	2.2	2.1	0.8

Table 10. Fe at Distance H = 0.3 m (1 ft) (PPG)

Source Radius (m)	Time after Detonation: 1 week	1 month	6 months
0.10	4.0	6.3	19.5
0.25	3.2	5.3	17.3
0.50	2.4	4.1	14.2
1	1.7	3.0	10.9
2	1.3	2.3	8.5
3	1.1	2.0	7.4
4	1.0	1.8	6.7
5	0.93	1.7	6.3
7	0.85	1.5	5.8
10	0.78	1.4	5.3
15	0.71	1.3	4.8
20	0.67	1.2	4.6
50	0.57	1.0	3.9
100	0.53	0.95	3.6
200	0.50	0.89	3.4
500	0.48	0.86	3.3

Table 11. Fe at Distance H = 0.5 m (NTS)

Source Radius (m)	Time after Detonation: 2 hours	4 hours	6 hours	12 hours
0.1	16.2	19.6	24.6	26.9
0.25	15.7	18.9	23.3	24.8
0.5	14.1	17.0	21.1	22.1
1	11.3	13.8	17.1	17.7
2	8.5	10.5	13.0	13.3
3	7.3	8.9	11.1	11.4
4	6.5	8.0	10.0	10.2
5	6.0	7.4	9.2	9.4
7	5.4	6.6	8.3	8.4
10	4.9	5.9	7.4	7.6
15	4.4	5.4	6.7	6.8
20	4.1	5.0	6.2	6.4
50	3.4	4.2	5.2	5.3
100	3.1	3.8	4.7	4.8
200	2.9	3.5	4.4	4.5
500	2.7	3.4	4.2	4.3

Table 12. Fe at Distance H = 1.0 m (NTS)

Source Radius (m)	Time after Detonation: 2 hours	4 hours	6 hours	12 hours
0.1	15.9	16.3	23.0	24.2
0.25	15.7	18.5	23.6	25.4
0.5	15.0	17.7	22.4	23.9
1	12.8	15.6	19.4	20.6
2	9.8	12.0	14.9	15.6
3	8.0	9.9	12.3	12.8
4	7.0	8.6	10.7	11.1
5	6.3	7.7	9.6	9.9
7	5.4	6.7	8.3	8.5
10	4.7	5.8	7.2	7.4
15	4.1	5.0	6.2	6.4
20	3.7	4.6	5.7	5.9
50	3.0	3.7	4.6	4.7
100	2.6	3.3	4.0	4.2
200	2.4	3.0	3.7	3.9
500	2.3	2.8	3.5	3.7

Table 13. Fe at Distance H = 1.0 m (PPG)

Source Radius (m)	Time after Detonation: 1 week	2 weeks
0.10	2.9	2.3
0.25	2.7	3.0
0.50	2.5	2.8
1	1.9	2.2
2	1.2	1.5
3	0.95	1.2
4	0.80	1.0
5	0.71	0.87
7	0.61	0.74
10	0.52	0.64
15	0.46	0.55
20	0.42	0.51
50	0.33	0.41
100	0.29	0.36
200	0.27	0.33
500	0.26	0.32

Table 14. Fe at Distance H = 2.0 m (NTS)

Source Radius (m)	Time after Detonation: 2 hours	4 hours	6 hours	12 hours
0.1	15.9	15.5	20.2	23.4
0.25	13.5	15.2	20.3	21.1
0.5	12.1	15.4	19.2	21.0
1	11.6	14.5	18.7	18.9
2	9.6	12.0	15.4	16.2
3	8.0	10.0	12.7	13.3
4	6.7	8.5	10.8	11.1
5	5.8	7.5	9.4	9.7
7	4.8	6.1	7.7	7.8
10	3.9	4.9	6.3	6.3
15	3.2	4.1	5.1	5.2
20	2.8	3.6	4.5	4.6
50	2.1	2.7	3.4	3.4
100	1.8	2.3	2.9	2.9
200	1.6	2.1	2.6	2.7
500	1.5	2.0	2.5	2.5

Due to the complexities of beta dose calculations, tables for applications not listed above are generated on a case-by-case basis.

5.3.3 Point Source

Similar to the method for point source dose to skin, calculations were performed for the lens of the eye. Examples of some scenarios involving eye exposures to point sources of beta and gamma radiation include inspecting the external surface of an aircraft that contains isolated “hot spots”, removing contaminated air filters collected during cloud sampling, and viewing small objects removed from contaminated target ships as specimens or souvenirs.

Beta dose rates to the lens of the eye from point sources of fallout beta radiation have been calculated using the aforementioned eye model with the CEPXS radiation transport code (Lorence et al., 1989). The source is modeled as a point from which beta radiation, having Finn spectral characteristics (Finn et al., 1979) is emitted isotropically. The point source is surrounded by a spherically symmetrical layer of air with radius R, which in turn is surrounded by the layers that comprise the eye. The energy deposited in the lens of the eye, as determined in this manner, is converted to a dose rate per unit activity (i.e., rad h^{-1} Ci^{-1}) in the point source by assuming 1 beta/decay.

The dose to the lens of the eye from a point source at 1 foot and 1 m as a function of time after a detonation and to skin at 1 foot and 1 m are presented in tandem in Tables II-2 and II-3 of Weitz, 2012.

5.3.4 Dermal Contamination on Eyelid

This section addresses dose to the lens of the eye caused by possible contamination deposited on the outer surface of the eyelid. It is therefore necessary to calculate the contamination dose to the eyelid as though a skin cancer was manifest, using the standard methods given in SM ED04.

Once the dermal contamination dose to the eyelid has been calculated, the dose to the lens of the eye from eyelid contamination can be calculated using the data in Table 15 (Weitz, 2012). Table 15 provides the ratio of the beta dose to the lens with respect to the beta dose in the basal cell layer of the eyelid as a function of time. The eyelid is assumed to have a thickness of 600 μm with the basal layer at a depth of 30 μm. The sensitive layer for the lens is assumed to be at a tissue depth of 3 mm. The radiation transport was performed with the CEPXS transport code (Lorence et al., 1989) and using the Finn beta spectral data (Finn et al., 1979; Weitz, 2012).

The corresponding beta dose to the lens is simply the beta dose to the eyelid multiplied by the Dose Ratio given in the last column of Table 15. As can be observed from Table 15, the dose to the lens of the eye if contamination of the eyelid occurred at H+12 hour is approximately 3.33 percent of the contamination dose to the eyelid and generally less during an Operation. The lens dose rises back to 3 percent at about 9 months to 1 year after a detonation (e.g., for possible post-operational decontamination activities).

Because it is likely that no eyelid contamination occurred to most personnel within several hours after the detonation (with the possible exception of cloud sampling aircraft crews or recovery personnel), most personnel did not accrue a lens dose from dermal contamination on the eyelid greater than 4.5 percent at any time after a detonation. Thus, the 4.5 percent is used as a default.

Table 15. Ratio of Lens Dose to Eyelid Dose

Time after Detonation	Avg beta energy (MeV)	Dose at 30 um in eyelid: MeV-cm2/g	Dose at 30 um in eyelid: rad/hr/beta/cm2-s	Dose at 3 mm in eye (lens): MeV-cm2/g	Dose at 3 mm in eye (lens): rad/hr/beta/cm2-s	Dose Ratio Lens:Eyelid
1 hr	0.824	5.01	2.89E-04	0.2388	1.38E-05	4.76E-02
2 hr	0.789	4.99	2.88E-04	0.2182	1.26E-05	4.37E-02
4 hr	0.767	4.98	2.87E-04	0.2092	1.21E-05	4.20E-02
6 hr	0.753	4.97	2.87E-04	0.2046	1.18E-05	4.11E-02
12 hr	0.679	4.95	2.85E-04	0.1647	9.49E-06	3.33E-02
1 d	0.539	4.88	2.81E-04	0.0896	5.16E-06	1.84E-02
2 d	0.425	4.80	2.77E-04	0.0393	2.27E-06	8.19E-03
3 d	0.370	4.76	2.74E-04	0.0232	1.34E-06	4.88E-03
1 wk	0.315	4.70	2.71E-04	0.0132	7.63E-07	2.82E-03
2 wk	0.317	4.70	2.71E-04	0.0150	8.66E-07	3.20E-03
1 mo	0.338	4.72	2.72E-04	0.0216	1.24E-06	4.58E-03
2 mo	0.347	4.70	2.71E-04	0.0335	1.93E-06	7.13E-03
4 mo	0.360	4.69	2.70E-04	0.0526	3.03E-06	1.12E-02
6 mo	0.388	4.70	2.71E-04	0.0728	4.19E-06	1.55E-02
9 mo	0.445	4.73	2.73E-04	0.1086	6.26E-06	2.29E-02
1 yr	0.504	4.77	2.75E-04	0.1436	8.27E-06	3.01E-02
2 yr	0.559	4.80	2.77E-04	0.1740	1.00E-05	3.62E-02

5.4 Beta Dose to Lens from Activation Products

Activation products are produced by neutron absorption in soil and other materials. The radioisotopes Na-24, Mn-56, Si-31, Ca-45, and K-42 are the primary contributors to the gamma and beta radiation in the vicinity of activated soil for the first few weeks after detonation, with Sc-46 and Co-60 at later times (e.g., months to years after the detonation.). Aluminum activation products decayed to immeasurable levels within minutes after a test detonation and, therefore, did not contribute to an eye dose by the time test participants approached the contaminated area.

External beta-to-gamma ratios for neutron activated products in soil are calculated using their respective parent elemental compositions and typical depths in soil with a density of 1.7 g cm^{-3}. Table 16 and Table 17 provide the resultant beta-to-gamma dose ratios.

Table 16. Beta-to-Gamma Lens Dose Ratio for Induced Radioactivity in Soil as a Function of Time and Height at NTS Area 7

Results for NTS Area 7:

Time after detonation (hours)	Beta/gamma eye dose ratio at eye height: 20 cm	40 cm	80 cm	100 cm	120 cm	160 cm	200 cm
0.5	0.0550	0.0496	0.0402	0.0362	0.0325	0.0263	0.0211
1	0.0537	0.0484	0.0393	0.0354	0.0318	0.0257	0.0207
2	0.0511	0.0461	0.0375	0.0337	0.0304	0.0246	0.0198
3	0.0483	0.0436	0.0355	0.0320	0.0289	0.0234	0.0189
4	0.0455	0.0411	0.0335	0.0303	0.0273	0.0222	0.0180
5	0.0427	0.0386	0.0316	0.0285	0.0258	0.0210	0.0171
6	0.0400	0.0362	0.0296	0.0268	0.0243	0.0199	0.0162
7	0.0374	0.0339	0.0278	0.0252	0.0228	0.0187	0.0154
8	0.0350	0.0318	0.0261	0.0237	0.0215	0.0177	0.0146
9	0.0329	0.0298	0.0246	0.0223	0.0203	0.0168	0.0138
10	0.0309	0.0280	0.0232	0.0211	0.0192	0.0159	0.0132
12	0.0276	0.0251	0.0208	0.0190	0.0173	0.0145	0.0121
15	0.0241	0.0220	0.0183	0.0168	0.0154	0.0129	0.0108
20	0.0209	0.0191	0.0160	0.0147	0.0135	0.0114	0.0097
24	0.0195	0.0178	0.0149	0.0137	0.0126	0.0107	0.0091
36	0.0172	0.0157	0.0131	0.0121	0.0111	0.0094	0.0080
48	0.0155	0.0141	0.0118	0.0109	0.0100	0.0085	0.0072
72	0.0128	0.0116	0.0096	0.0088	0.0081	0.0069	0.0058
120	0.0087	0.0078	0.0064	0.0058	0.0053	0.0045	0.0038
168	0.0061	0.0054	0.0043	0.0039	0.0035	0.0030	0.0025

Table 17. Beta-to-Gamma Lens Dose Ratio for Induced Radioactivity in Soil as a Function of Time and Height at NTS Frenchman Flat

Results for NTS Frenchman Flat:

Time after detonation (hours)	Beta/gamma eye dose ratio at eye height: 20 cm	40 cm	80 cm	100 cm	120 cm	160 cm	200 cm
0.5	0.0509	0.0457	0.0369	0.0331	0.0297	0.0238	0.0191
1	0.0493	0.0443	0.0358	0.0321	0.0288	0.0231	0.0185
2	0.0461	0.0414	0.0334	0.0300	0.0270	0.0217	0.0174
3	0.0427	0.0384	0.0310	0.0279	0.0251	0.0202	0.0162
4	0.0394	0.0354	0.0286	0.0257	0.0231	0.0187	0.0150
5	0.0360	0.0324	0.0262	0.0236	0.0212	0.0172	0.0138
6	0.0329	0.0296	0.0240	0.0216	0.0194	0.0157	0.0127
7	0.0299	0.0269	0.0218	0.0196	0.0177	0.0144	0.0117
8	0.0271	0.0244	0.0198	0.0179	0.0161	0.0131	0.0107
9	0.0246	0.0222	0.0180	0.0163	0.0147	0.0120	0.0098
10	0.0224	0.0202	0.0164	0.0148	0.0134	0.0110	0.0090
12	0.0188	0.0169	0.0138	0.0125	0.0113	0.0094	0.0077
15	0.0151	0.0136	0.0111	0.0101	0.0092	0.0077	0.0064
20	0.0119	0.0107	0.0088	0.0080	0.0073	0.0062	0.0052
24	0.0107	0.0096	0.0079	0.0072	0.0066	0.0056	0.0047
36	0.0092	0.0083	0.0068	0.0062	0.0057	0.0048	0.0041
48	0.0084	0.0075	0.0061	0.0056	0.0051	0.0043	0.0037
72	0.0070	0.0062	0.0050	0.0045	0.0041	0.0035	0.0030
120	0.0050	0.0043	0.0034	0.0031	0.0028	0.0023	0.0020
168	0.0037	0.0032	0.0024	0.0021	0.0019	0.0016	0.0014

Beta and gamma doses to the lens of the eye are calculated in an identical manner as for external skin dose from activation products by replacing the beta-to-gamma dose ratios for skin with those specified for the lens of the eye given above.

6. Data and Input

Operation and shot-specific data are compiled in SOP Appendices A–C.

7. Referenced SOPs and Standard Methods from this Manual

(1) SOP RA01 - Radiation Dose Assessments for Cases Requiring Detailed Analysis

(2) SM ED02 - Whole Body External Dose Assessment

(3) SM ED03 - Skin Dose from External Sources

(4) SM ED04 - Skin Dose from Dermal Contamination

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