Determining Total Effective Dose at Nevada National Security Site Aerially Dispersed Radiological Release Sites - 11155

R.L. Kidman*, P. Matthews*, K. Cabble**, and R. Boehlecke**
*Navarro-Intera, LLC, Las Vegas, Nevada 89193
**U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office
Las Vegas, Nevada 89193

ABSTRACT

The risk-based corrective action process implemented by Nevada National Security Site (NNSS) Environmental Management (EM) soil remediation activities uses total annual dose as a measure of risk to potential receptors. The U.S. Department of Energy (DOE) Order 5400.5 establishes a basic dose limit of 1 millisieverts per year (mSv/yr) and a dose constraint of 0.25 mSv/yr (in excess of background). The need for corrective action under the *Federal Facility Agreement and Consent Order* is determined at NNSS EM soil sites based on the 0.25-mSv/yr dose constraint as received by a potential site receptor. While the dose rate at a contaminated site is relatively constant and continues throughout the year, the annual dose a potential receptor receives from the contaminated site is dependent upon the cumulative annual exposure time (during which the receptor is present at the site and exposed to the contamination). Therefore, measurements of dose rate at a contaminated site must be converted to an annual potential dose using an assumed annual exposure time. For the NNSS EM soils activities this is done by establishing three standard exposure scenarios: Industrial Area, Remote Work Area, and Occasional Use Area. These standard exposure scenarios assume different exposure durations based on present and forecasted land use. The need for corrective action is based on determining whether a potential receptor could receive a 0.25-mSv dose during the annual exposure duration of the appropriate land use scenario. If the actual land use of the contaminated site should change, the risk to potential receptors will need to be re-evaluated and, if necessary, corrective actions will need to be implemented to ensure workers do not receive an annual dose exceeding 0.25 mSv.

Estimation of the annual dose was accomplished by estimating the internal and external dose components of total dose separately. The estimates of internal dose rates were derived through sampling of sieved surface soil, analysis of the samples for radiological isotopes, and calculation of the internal dose from isotopic results using the Residual Radioactive computer code. The estimates of external dose at the various test plots were derived using thermoluminescent dosimeters (TLDs). The corrective action decision level is only applicable to radiation exposure from man-made sources at the NNSS and is a value in excess of the radiation exposure that would be present if no nuclear activities had been conducted at the site (i.e., from natural background radiation). Estimates of external dose, in millirem per Industrial Area year, were presented as net values (i.e., dose due to natural background radiation has been subtracted from the total external dose result). Natural background external radiation was registered on TLDs placed in areas determined to be unaffected by man-made activities at the NNSS.

INTRODUCTION

The information needed to evaluate dose to a potential receptor from contaminant releases associated with NNSS EM soil sites is generated under a *Federal Facility Agreement and*

Consent Order [1] corrective action investigation. This investigation is conducted to generate the information necessary to meet the following objectives:

- Identify contamination present at the site that exceeds the corrective action decision level (CADL).
- Define the corrective action boundary as the area that exceeds the CADL.

DOE Order 5400.5 requires that: "Authorized Limits shall be established to (1) provide that, at a minimum, the basic dose limits … will not be exceeded, or (2) be consistent with applicable generic guidelines" [2]. The basic dose limit is 1 mSv/yr with a dose constraint established with stakeholders at 0.25 mSv/yr. The CADL that has been agreed to by stakeholders for use at NNSS EM soil sites is a dose of 0.25 mSv/yr (in excess of background) to the most exposed potential receptor [3].

The first environmental decision for any soil site is to determine whether contamination exceeding the CADL exists at the site. If contamination exceeding the CADL exists at the site, the next environmental decision is to determine the extent of the area that exceeds the CADL (i.e., the corrective action boundary). The data needed for this determination is a measurement of the annual potential total effective dose (TED) at specific locations that will support the environmental decision. For example, an environmental decision that TED does not exceed the CADL would require that the TED be measured at the location(s) most likely to present the maximum dose. As measured dose is only an estimate of the true dose at the site, the 95 percent upper confidence limit (UCL) of the mean of dose measurements at each location was used for decision-making.

The true dose rate at a contaminated site is relatively constant and continues throughout the year. However, the annual dose a potential receptor receives from the contaminated site is dependent upon the cumulative annual exposure time (during which the receptor is present at the site and exposed to the contamination). Therefore, measurements of dose rate at a contaminated site must be converted to an annual potential TED using an assumed annual exposure time. For the NNSS, this is done by establishing three standard exposure scenarios [3]:

Industrial Area – This scenario addresses industrial workers exposed daily to contaminants in soil during an average workday. This scenario assumes that this is the regular assigned work area for the worker who will be on the site for an entire career (225 days per year [day/yr], 10 hours per day [hr/day] for 25 years). The TED values calculated using this exposure scenario is the TED an industrial worker receives during 2,250 hours of annual exposure to site

Remote Work Area – This exposure scenario assumes non-continuous work activities at a site. This scenario addresses industrial workers exposed to contaminants in soil during a portion of an average workday. This scenario assumes that this is an area where the worker regularly visits but is not an assigned work area where the worker spends an entire workday. A site worker under this scenario is assumed to be on the site for an equivalent of 336 hr/yr (or 42 day/yr) for an entire career (25 years). The TED values calculated using this exposure scenario are the TED a remote area worker receives during 336 hours of annual exposure to site radioactivity.

Occasional Use Area – This exposure scenario assumes occasional work activities at a site. This scenario addresses exposure to industrial workers who are not assigned to the area as a regular worksite but may occasionally use the site. This scenario assumes that this is an area where the worker does not regularly visit but may occasionally use for short-term activities.

A site worker under this scenario is assumed to be on the site for an equivalent of 80 hours (or 10 days) per year, for 5 years. The TED values calculated using this exposure scenario are the TED an occasional use worker receives during 80 hours of annual exposure to site radioactivity.

The determination of the appropriate exposure scenario is based on an assumption of actual and/or forecasted land use. Any corrective action decisions based on this assumption will need to be re-evaluated if actual land use were to change.

SEPARATE ESTIMATES OF INTERNAL DOSE AND EXTERNAL DOSE

The annual potential TED from surface contamination due to aerially dispersed radiological releases was determined from independent measurements of internal and external dose (TED from other types of radiological contamination is determined using other techniques that are not discussed herein). The TED at these types of soil release locations was determined by summing the internal and external dose components. Internal dose was calculated from soil sample results, and external dose was determined by collecting *in situ* measurements using TLDs. These separate dose calculations were necessary due to the presence of Trinity glass particles at some sites. These particles contribute significantly to external dose but are too large to contribute to internal dose (i.e., they are not amenable to inhalation or ingestion). An additional problem in estimating internal dose for these particles was that they were resistant to the digestion techniques required by the radiochemical analysis procedures.

The estimates of TED at the various sample plots involved adding independent estimates of internal and external doses. As shown in Table I, at some Soils Project release sites, internal dose has comprised less than 1 percent of the TED while at other release sites, TED comprises primarily internal dose. This variable proportion of internal and external dose is due to the following factors:

- The amount of nuclear yield relative to the amount of nuclear material in the device (i.e., efficiency). As most of the nuclear source material in efficient devices reacts during detonation, the source nuclear material is mostly converted into fission products. Efficient devices result in contamination that is composed primarily of gamma-emitting radionuclides and, therefore, external dose is expected to be the major component of TED. Low-efficiency nuclear tests (such as safety tests) have little or no yield. This results in the release and dispersal of the source nuclear material. The resulting contamination has a significant alpha component and, therefore, internal dose is expected to be the major component of TED.
- The composition of source materials used in the nuclear device. Nuclear devices containing plutonium (Pu) fuel result in higher residual internal/external dose ratios in soil than devices containing only uranium (U).

Table I. Fraction External Dose at Various Soils Project Sites

Corrective Action Unit	Site	Fraction External Dose	Comments
367	Sedan	93–99%	Plowshare U device
370	T-4	96–100%	Weapons-related U device
371	Johnnie Boy	99–100%	Weapons-effects U device
371	Pin Stripe	99–100%	Surface venting from underground test
372	Cabriolet	75–88%	Plowshare Pu device
372	Little Feller I	24–48%	Weapons-effects Pu device
372	Little Feller II	15–46%	Weapons-effects Pu device
372	Palanquin	85–88%	Plowshare Pu device

EXTERNAL DOSE ESTIMATE

External dose (penetrating radiation dose for the purpose of this document) was determined by collecting *in situ* measurements using TLDs. The TLD placement and processing followed the protocols established in the *Nevada Test Site Routine Radiological Environmental Monitoring Plan* [4]. The TLDs are placed 3 feet above the ground surface and measure the total radiation from all *in situ* materials independent of particle size, type, and configuration. This provides a representative measure of the actual contribution to external dose from the Trinity glass aggregates or large particles that are not included in the analytical soil samples.

The total TLD exposure time is designed to exceed the number of hours per year that a potential receptor could be present at the site. This is normally based on the Industrial Area exposure scenario. The dose measured by the TLD measurements is normalized to the annual exposure time of the appropriate exposure scenario by dividing the TLD dose by the actual TLD exposure hours, and multiplying by the annual exposure hours of the appropriate exposure scenario.

The CADL is only applicable to radiation exposure from man-made sources at the NNSS and is a value in excess of the radiation exposure that would be present if no nuclear activities had been conducted at the site (i.e., from natural background radiation). Therefore, estimates of external dose are presented as net values (i.e., dose due to natural background radiation has been subtracted from the total external dose result). To avoid underestimating external dose by subtracting too much background radiation, at least four TLDs are placed at locations beyond any detectable influence of the release being investigated as determined by radiation survey results. In addition, the natural background external radiation is conservatively estimated by using the minimum dose measured from any TLD.

The determination of the external dose component of the TED by TLDs was determined to be the most defensible method because the use of a TLD to determine an individual's external exposure is the standard in radiation safety and serves as the "legal dose of record" when other measurements are available. The project-specific TLDs are subjected to the same quality assurance (QA) checks as the routine NNSS environmental monitoring TLDs.

INTERNAL DOSE ESTIMATE

Larger particles (e.g., Trinity glass [Fig. 1]) are excluded from soil samples used to estimate the internal dose portion of the TED. The larger particles, including the non-friable Trinity glass aggregates, were separated from the sampled material by passing the sample through a #4 sieve (Fig. 2). Soil samples used to calculate internal dose at each location were designed to represent an area of 100 square meters (m^2) (i.e., a 10 × 10 meter [m] sample plot). Analytical results from homogenized soil samples were used to calculate the internal dose using the Residual Radioactive (RESRAD) model and computer code, version 6.4 [5]. Input parameters appropriate to the NNSS used in this model were established with stakeholders.

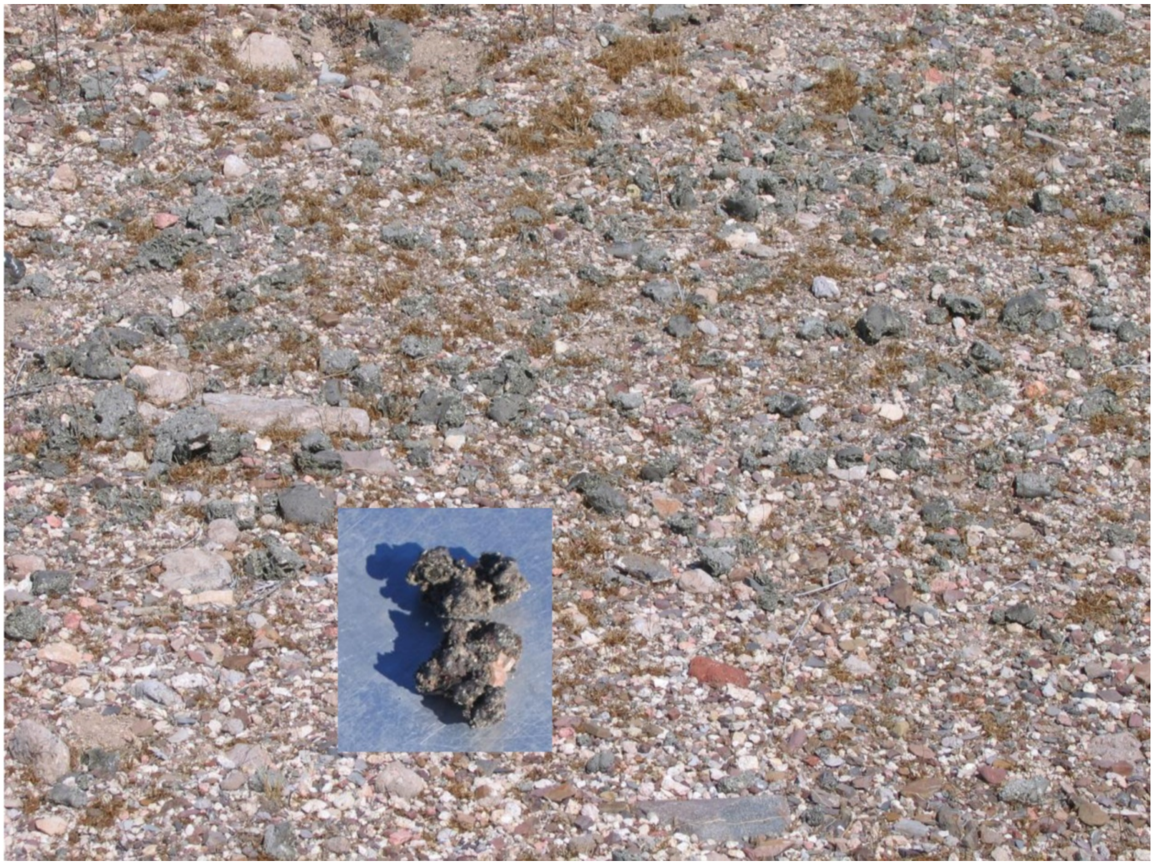

Fig. 1. Trinity glass.

Fig. 2. Collection of soil samples.

Statistical methods that generate site characteristics were used for establishing internal dose values that represent the sample plot as a whole. Composite samples were collected at each sample plot in the following manner:

- Each composite sample was composed of nine aliquots taken from locations within each plot. These locations were predetermined using a random start with a triangular grid pattern.
- Each composite sample was collected from 0 to 5 centimeters (cm) below ground surface. The depth of 5 cm was selected based on previous investigations which found that radionuclides with multiyear half-lives deposited from aboveground nuclear testing at the NNSS are concentrated in the upper 5 cm of undisturbed soil [6, 7, 8, 9, and 10].
- Samples were sieved to eliminate material (e.g., Trinity glass) greater than 6.4-millimeter diameter that cannot effectively be inhaled or ingested (see Fig. 1).
- The entire volume of the composited material collected was submitted to the laboratory for analysis.

Spatial Variability

The measurement of internal dose can be affected by individual radioactive particles. Where these particles are not homogeneously distributed across any particular area, point measurements of internal dose may indicate a much higher or lower dose than that actually received by a receptor (that is not limited to one particular point and whose received dose is essentially an integration of point doses over the entire area of exposure). The U.S. Environmental Protection Agency (EPA) has addressed this issue by issuing guidance to average the exposure concentrations over an area of exposure [11]. The EPA guidance states the following:

> *An exposure point (also called an exposure area or exposure unit) is a location within which an exposed receptor may reasonably be assumed to move at random and where contact with an environmental medium (e.g., soil) is equally likely at all sub locations…. An exposure point concentration (EPC) is an estimate of the true arithmetic mean concentration of a chemical in a medium at an exposure point.*

The EPA's Human Health Evaluation Manual [12] states the following:

> *In some cases, contamination may be unevenly distributed across a site, resulting in hot spots (areas of high contamination relative to other areas of the site)…. The area over which the activity is expected to occur should be considered when averaging the monitoring data for a hot spot. For example, averaging soil data over an area the size of a residential backyard (e.g., an eighth of an acre) may be most appropriate for evaluating residential soil pathways.*

While the use of an exposure area (or point dose measurements) would not produce a realistic estimate of total dose received by a receptor (that may result in a false positive decision error), use of an exposure area that is too large may unrealistically underestimate the total dose received (and may result in a false negative decision error). To control both of these types of errors, the NNSS used an exposure area of 100 m^2 (i.e., a 10 × 10 m sample plot). While this area is much smaller than the area where a receptor may reasonably be assumed to move during normal work activities (resulting in a conservative estimate of internal dose), it is large enough to integrate the effects on internal dose of small particles of high specific activity.

Estimating internal dose from soil samples is problematic due to the particle nature of Pu (where particles may be non-uniformly distributed within soil samples) and the relatively small aliquots used for isotopic Pu analyses (that may not capture the discrete Pu particles). An individual Pu particle in a small isotopic Pu soil sample (typically, 1 gram [g] of soil) can significantly influence the resulting analytical result for Pu isotope concentrations and, therefore, the internal dose estimate. It is common for Pu sample results from duplicate samples to not meet precision criteria as the distribution of Pu in soil has been found to vary by a factor of 10 between individual 1-g aliquots from a single soil sample [13]. A larger sample volume would increase the likelihood that Pu analytical results would be representative of the sampled location (i.e., reduce the influence of an individual particle on sample concentration). However, it is not practical for the analytical laboratory to digest a large volume of soil.

To improve the estimate of isotopic Pu concentrations, the NNSS infers the concentrations of Pu isotopes in each sample using americium (Am) as a surrogate. This is done by measuring the Am concentration in a 1-liter (L) soil sample using the gamma spectroscopy analytical method. The Pu to Am ratios are established from isotopic analyses (average ratios from the 1-g soil sample results of Am, Pu-238, and Pu-239/240). The Pu to Am ratio should be fairly constant based on the ratio of these materials in the test device and the rate of radioactive decay since the release. This increased “field of view” using a larger sample volume should reduce the effects of individual particles on results when compared to the 1-g analysis sample volumes (such as used for isotopic Pu). The resulting gamma measurement of Am-241 from the 1-L sample was then used to generate an integrated gamma-derived Pu concentration estimate by multiplying the gamma Am-241 result from the 1-L sample by the Pu to Am-241 ratios based on the Pu and Am isotopic analytical results.

Internal dose was calculated from radiochemical results using the “sum of fractions” method described in Appendix I to Title 10 *Code of Federal Regulations* 73 [14].

$$\sum_{1}^{n}\left[\frac{R_1}{AR_1}+\frac{R_2}{AR_2}+\frac{R_n}{AR_n}\right] \qquad \text{(Eq. 1)}$$

Where:

R_1 = activity for radionuclides or source number 1
R_2 = activity for radionuclides or source number 2
R_N = activity for radionuclides or source number n
AR_1 = activity limit for radionuclides or source number 1
AR_2 = activity limit for radionuclides or source number 2
AR_N = activity limit for radionuclides or source number n

The estimates of dose were based on the added contribution to dose from each of the radionuclides present in any analytical sample at levels exceeding a screening action level. Each radionuclide analytical result was converted to represent a fraction of the 0.25 mSv/yr CADL. This was done by dividing the analytical result by the concentration of that radionuclide required to generate a dose equal to the CADL. The fractions thus calculated for each of the radionuclides were then added using the sum of fractions method. A sample with a sum of fractions greater than one was considered to exceed the CADL.

The activity limits used in the above equation for each radionuclide were calculated using the RESRAD computer code [5] as the concentration of the radionuclide in soil that would cause a potential receptor to receive an annual internal dose of 0.25 mSv independent of the presence of any other radionuclide. The calculation of the activity limit was also based on the appropriate standard exposure scenario.

Calculation of internal dose at TLD locations

At sites where internal dose is not the major component of TED, internal dose is conservatively estimated for TLD locations where soil samples have not been collected. This is accomplished using two methods depending upon the significance of internal dose at the release site.

Method 1

- This method is applicable to sites where external dose is the predominant contributor to total dose. The internal dose used for all TLD locations is conservatively estimated to be equal to the maximum internal dose calculated at any sample plot.

Method 2

- This method is applicable to sites where internal dose is significant but not the predominant component of TED. The ratio between the internal and external dose is calculated for the sample plot with the maximum internal dose. This internal/external dose ratio is multiplied by the external dose calculated from each TLD location to conservatively estimate the internal dose for that location.

SUMMARY

At aerially dispersed radiological release sites, the annual potential TED from surface contamination can be simplified by making conservative assumptions about the following:

- The potential exposure duration of the most exposed receptor (develop an appropriate exposure scenario)
- The potential for significant internal dose (based on the type of device and efficiency of the device)

If the potential for significant internal dose is low, soil sample numbers can be reduced by assuming that the maximum internal dose is present at all TLD locations. If the potential for significant internal dose is moderate, soil sample numbers can be reduced by assuming that the internal/external dose ratio at the location of the maximum internal dose is applicable to all TLD locations. The internal dose at each TLD location is then established using the measured external dose and the internal/external dose ratio.

If the potential for significant internal dose due to Pu particles is present, the spatial variability of the non-uniformly distributed particles can result in significant internal dose measurement errors. These errors were reduced by characterizing a 100-m^2 exposure area, homogenizing multiple aliquots into each sample, eliminating larger particles such as Trinity glass, and inferring Pu concentrations. The Pu concentrations were inferred from gamma spectroscopy measurements of Am using a large sample size and the average Pu/Am ratio based on isotopic analyses from common soil samples.

Use of these techniques has resulted in higher confidence in TED measurements and in reduced sampling requirements at soil sites.

REFERENCES

1. FEDERAL FACILITY AGREEMENT AND CONSENT ORDER, Agreed to by the State of Nevada; U.S. Department of Energy, Environmental Management; U.S. Department of Defense; and U.S. Department of Energy, Legacy Management (1996; as amended March 2010).

2. U.S. DEPARTMENT OF ENERGY, *Radiation Protection of the Public and the Environment*, DOE Order 5400.5, Change 2 (1993).

3. U.S. DEPARTMENT OF ENERGY, NATIONAL NUCLEAR SECURITY ADMINISTRATION NEVADA SITE OFFICE, *Industrial Sites Project Establishment of Final Action Levels*, Rev. 0, DOE/NV--1107 (2006).

4. U.S. DEPARTMENT OF ENERGY, NATIONAL NUCLEAR SECURITY ADMINISTRATION NEVADA SITE OFFICE, *Nevada Test Site Routine Radiological Environmental Monitoring Plan*, DOE/NV/11718--804, prepared by Bechtel Nevada (2003).

5. C. YU, A.J. ZIELEN, J.J. CHENG, D.J. LEPOIRE, E. GNANAPRAGASAM, S. KAMBOJ, J. ARNISH, A. WALLO III, W.A. WILLIAMS, and H. PETERSON, *User's Manual for RESRAD Version 6*, ANL/EAD-4 (Version 6.4 released in December 2007), Environmental Assessment Division (2001).

6. E.H. ESSINGTON, "Soil Investigations for the Nevada Applied Ecology Group: A Historical Review and Current Status," in *The Dynamic of Transuranics and Other Radionuclides in Natural Environments*, NVO-272, W.A. Howard and R.G. Fuller eds., U.S. Department of Energy, Nevada Operations Office (1985).

7. R.D. MCARTHUR and J.F. KORDAS. *Nevada Test Site Radionuclide Inventory and Distribution Program: Report #2, Areas 2 and 4,* DOE/NV/10162-20 (1985).

8. R.D. MCARTHUR and J.F. KORDAS. *Radionuclide Inventory and Distribution Program: The Galileo Area,* DOE/NV/10162-14, Desert Research Institute, University of Nevada System, Water Resources Center (1983).

9. R.O GILBERT, E.H. ESSINGTON, D.N. BRADY, P.G. DOCTOR, and L.L EBERHARDT. "Statistical Activities During 1976 and the Design and Initial Analysis of Nuclear Site Studies," in *Transuranics in Desert Ecosystems,* NVO-181, Nevada Applied Ecology Group (1977).

10. T. TAMURA. "Plutonium Distribution in a Desert Pavement-Desert Mound Soil System in Area 11," in *Environmental Plutonium on the Nevada Test Site and Environs,* NVO-171, Nevada Applied Ecology Group, U.S. Energy Research and Development Administration (1977).

11. U.S. ENVIRONMENTAL PROTECTION AGENCY, *Guidance on Systematic Planning Using the Data Quality Objectives Process, EPA QA/G-4, EPA/240/B-06/001,* Washington, DC: Office of Environmental Information (2006).

12. U.S. ENVIRONMENTAL PROTECTION AGENCY, *Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual (Part A)*, EPA/540/1-89/002, Washington, DC: Office of Emergency and Remedial Response (1989).

13. W. BLISS and L. DUNN. "Measurement of Plutonium in Soil around the Nevada Test Site," in *Proceedings of the Environmental Plutonium Symposium, Held at LASL, August 4-5, 1971,* Los Alamos Scientific Laboratory of the University of California (1971).

14. CODE OF FEDERAL REGULATIONS, Title 10 CFR Part 73, Appendix I, "Category 1 and 2 Radioactive Materials," Washington, DC: U.S. Government Printing Office (2010).

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