

ATTACHMENT B BIOLOGICAL PROPERTIES OF TRITIUM AND TRITIUM HEALTH PHYSICS

(Note: With the exception of Sections B.5.1.1.1, B.5.1.1.2, and B.5.1.1.3, the bulk of the material presented in this attachment was adapted from Sections 3 and 4 of the U.S. Department of Energy's "Health Physics Manual of Good Practices for Tritium Facilities" (DOE, 1991). Although some of the information may appear to be somewhat dated, the basic concepts behind the information have not changed since that time.¹ See also the information presented in Attachment A.)

B.1 Biological Properties of Tritium

B.1.1 General

Tritium is usually encountered in the workplace as tritium gas (HT, DT, or T₂) or as tritiated water, or water vapor (i.e., HTO, tritiated heavy water (DTO), or T₂O). Other forms of tritium also exist, such as tritiated surfaces, metal tritides, tritiated pump oil, and tritiated gases. While some minor isotopic differences in reaction rates have been noted, deuterated and tritiated compounds generally have the same biological properties as the hydrogenated compounds. These various tritiated compounds will have a wide range of uptake and retention in humans under identical exposure conditions. Tritium gas, for example, represents one end of the spectrum, in that the body has no physiological use for elemental hydrogen regardless of its isotopic form and can easily be exhaled. Water vapor, on the other hand, represents the opposite end of the spectrum because it is readily taken up and retained by the body. Less is known about the uptake and retention of other tritiated compounds.

B.1.2 The Metabolism of Gaseous Tritium

The biological mechanisms for inhalation exposure to gaseous tritium are similar to the biological mechanisms for airborne nitrogen: (i) small amounts of the gas will be dissolved in the bloodstream according to the laws of partial pressures, (ii) the dissolved gas will be circulated in the bloodstream with a resident half-time of about 2 minutes, and (iii) most of the gas will subsequently be exhaled along with the gaseous waste products carbon dioxide and normal water vapor. A small percentage of the gaseous tritium will be converted to the oxide form (HTO), most likely in the gastrointestinal tract. Early experiments showed that the total biological conversion to HTO can range from 0.004 percent to 0.1 percent of the total gaseous tritium inhaled. More recent experiments with six volunteers resulted in a conversion of 0.005 percent with an uncertainty in the average conversion rate of ± 0.0008 percent.

Skin absorption of gaseous tritium has been found to be negligible when compared to inhalation. Small amounts of tritium can enter skin through contact with contaminated surfaces and result in elevated organically bound tritium in tissues and in urine (see Sections B.1.4 and B.1.5). Hence, for gaseous tritium exposures, there is a lung dose from the tritium in the air in the lung, and a whole body dose from the tritium gas that has been converted to water. This in vivo converted tritiated water will, of course, act like an exposure to tritiated water.

¹ Additional Note: Because the bulk of the information presented in this attachment is presented in a paraphrased format, it is suggested that the reader refer directly to DOE 1991 for additional information, which does include all the references to the original citations.

B.1.3 The Metabolism of Tritiated Water

The biological incorporation (uptake) of airborne HTO can be extremely efficient—up to 99 percent of inhaled HTO can be taken into the body within seconds. Ingested liquid HTO is almost completely absorbed by the gastrointestinal tract and quickly appears in the venous blood. Within minutes, it can be found in varying concentrations in the various organs, fluids, and tissues of the body. Skin absorption mechanisms also become important because the internal temperature of the body is regulated, to a large extent, by “breathing” water vapor in and out through the pores of the skin. For skin temperatures in the range of 30 to 40 °C, it has been shown that the percutaneous absorption of HTO is about equal to that for HTO by inhalation. Thus, it can be expected that, independent of the absorption mechanism, absorbed HTO will be uniformly distributed in all biological fluids in time frames that range from 45 minutes to 2 hours. Therefore, very shortly after an exposure to HTO, the tritium will be uniformly spread throughout the tissue of the body in body water and in the exchangeable (labile) hydrogen sites in organic molecules. This tritium will have a retention that is characteristic of water. A small fraction of the tritium will become incorporated into nonexchangeable hydrogen sites in organic molecules, giving rise to a long-term retention that is characteristic of the turnover of cellular components, which can be adequately modeled as the sum of two exponentials. Hence, retention of tritiated water can be described as the sum of two exponentials, one characteristic of body water, and two longer-term components that represent tritium incorporated into nonlabile cellular hydrogen sites.

B.1.4 The Metabolism of Other Tritiated Species

As mentioned above, most tritium will be in the form of tritiated hydrogen gas or tritiated water. However, tritium-handling operations will result in the production of other forms of tritium, such as tritiated surfaces, metal tritides, pump oils, and a wide variety of “other” tritiated species, some of which are discussed below.

B.1.4.1 Tritiated Surfaces

Studies have shown that when there is contact between skin and a surface that has been exposed to high concentrations of tritium gas, tritium is transferred to the body in an organic form. This organically bound tritium gives rise to elevated tritium concentrations in skin at the point of contact and in other tissues, and a large amount of organically bound tritium in urine. The full metabolic pathway of this organically bound tritium is unknown, but models that have been developed suggest that the dose to skin at the point of contact is the limiting factor in exposures of this type.

B.1.4.2 Metallic Tritides

Although a broad spectrum of metals is commonly used for the storage, pumping, and packaging of tritium, there is little data on their metabolic properties. However, some compounds are unstable in air (e.g., uranium tritide, lithium tritide). For these, exposure to air produces totally different results: uranium tritide, being pyrophoric, releases large quantities of tritiated water; lithium tritide, being a hydroxyl scavenger, releases large quantities of tritium gas.

At the other end of the spectrum, metallic tritides such as titanium, niobium, and zirconium tritides are very stable in air. For these, the organ of concern must be primarily the lung, and one relies on lung deposition models such as the one presented in the International

Commission on Radiological Protection's Publication 30 (ICRP-30) (ICRP, 1979). However, there are difficulties with using such models. Depending on the particle size distribution of the metallic tritide inhaled, lung-retention estimates can be in error by up to 80 percent. Also, cross-correlations of lung-retention estimates are based on the tritium leaching ability of biological fluids, which are dependent on the chemical and physical form of the material in question. These particles may also produce organically bound tritium from contact with lung tissue, and this would further compound the metabolic uncertainties.

B.1.4.3 Generic Tritiated Solids

The formation of generic tritiated solids can be expected to occur in all normal solid materials that are routinely exposed to tritium. Depending on the composition of the material, tritiation will occur through exchange reactions and/or through mechanisms such as solubility, permeation, and diffusivity. The specific activity of such materials can be expected to vary in relation to the relative concentration of the exposing gas, the relative humidity of the exposing gas, and the total reaction time. Radiation damage may also be expected, particularly in cases where possible exposure mechanisms lead to embrittlement.

Because little is known about the metabolic behavior of generic tritiated solids, each must be considered separately. For example, solid materials that tend to become embrittled should be considered in the same metabolic category as metallic tritides. Such materials would include, but not be limited to, Teflon™ valve seats (from dry environs). Other materials, such as those that degrade over time or those that give up their tritium easily (outgas), can be considered as possible inhalation hazards, possible skin absorption hazards, or both.

B.1.4.4 Tritiated Liquids

Next to HTO, the most commonly encountered tritiated liquid is tritiated vacuum pump oil. Comparisons between facilities have shown that the specific activities of pump oils can easily range from a few millicuries per liter to a few tens of curies per milliliter. The wide range in specific activities may be due to situation-specific variations in total throughputs for tritium and ambient water vapor. As a first approximation, the metabolic routes for tritiated vacuum pump oils can be taken as being similar to the metabolic routes for HTO.

Next to pump oils, the most commonly encountered group of tritiated liquids is tritiated solvents. Since all solvents, by their nature, can be expected to have a skin absorption pathway, and since most solvents are relatively volatile, the metabolic pathways for tritiated solvents can, as a first approximation, be expected to be similar to the pathways for HTO. However, families of solvents have specific organs of concern and, in most cases, the initial organ of interest will not be the body water, but the liver. Hence, exposure to tritiated solvents may result in significant differences between the establishment of body water equilibria from that observed for tritiated water.

The error in uptake and retention introduced by treating tritiated liquids as HTO will vary greatly with the individual chemical form.

B.1.4.5 Tritiated Gases

Although few gaseous reactions can compete with the energetically favored formation of HTO, other tritiated gases, such as tritiated methane, can be formed. The details of the metabolic

pathways should be generally similar to gaseous tritium. Again, the errors introduced by this approximation are unknown.

B.1.5 Metabolic Elimination

B.1.5.1 Single-Compartment Modeling of HTO Retention

Studies of biological elimination rates in humans for heavier-than-normal water species go back to 1934, when the body water turnover rate of a single subject was measured using hydrogen-deuterium oxide (HDO). Since that time, several additional studies have been conducted on a number of subjects with HDO and HTO, the HTO studies being more prevalent. Table B-1 presents a summary of these data.

Table B-1 Heavier-than-Normal Biological Half-Life

Water species	Number of subjects	Measured T _{Bio} (days)
HDO	1	9 to 10
HDO	21	9.3 ±1.5
HTO	8	9 to 14
HTO	20	5 to 11
HTO	8	9.3 to 13
HTO	10	7.5 ±1.9
HTO	5	9.5 (average)
HTO	6	8.5 (average)
HTO	310	9.5 ±4.1

A simple average of the data summarized in Table B-1 suggests a value of 9.4 days for the measured biological half-life. Also, the data deviate from this simple average by as much as ±50 percent. As is discussed below, there are good reasons for such large deviations.

As a first approach to modeling the observed biological half-life, one can use Equation B.1:

$$A = A_0 e^{-(\ln 2 t)/(T_{\text{Bio}})}, \quad (\text{B.1})$$

where A_0 is the total body water mass, A is the amount of body water remaining after a given time (t), and T_{Bio} is the biological half-life.

From reference man data (i.e., ICRP Publication 25 (ICRP-25) (ICRP, 1977)), values of 42 kilograms (kg) and 3 kg are obtained for the total body water mass and the average daily throughput of water, respectively. Thus, the elimination rate is $3/42 = 0.0714 \text{ day}^{-1}$, and the theoretical biological half-life for HTO is as shown in Equation B.2:

$$T_{\text{Bio}} = \ln 2 / 0.0714 = 9.7 \text{ days}, \quad (\text{B.2})$$

which compares very favorably with the 9.4-day average value determined from Table B-1.

The above modeling and values are also based on the assumption that the biological half-life of tritium will be a function of the average daily throughput of water. This part of the hypothesis, therefore, must also be in agreement with experimental and theoretical crosschecks.

It has been observed experimentally that, when the water intake was 2.7 liters per day, the half-life for HTO was 10 days; when the water intake was increased to 12.8 liters per day, the half-life dropped to 2.4 days. Using these values, Equation B.1 produces values of 10.4 days and 1.9 days for the respective half-lives. Agreement of experimental observations with the simple model is very good, and for the high-intake value, the lack of better agreement should not be a serious concern considering model simplicity. Without medical intervention (i.e., diuretics), the metabolic efficiency of the processes of forced fluids can require modification of the model. Other factors that affect the biological half-life of HTO in the human body are discussed below.

Comparisons have also been made of biological half-lives versus mean outdoor temperatures at the time of tritium uptake. The data suggest that biological half-lives are shorter when assimilations occur in the warmer months. For example, the 7.5 ± 1.9 -day half-life shown in Table B-1 begins to fall into line when it is noted that the data were taken in Southern Nigeria, where the mean outdoor temperature averages 80 °F. In contrast, the 9.5 ± 4.1 -day half-life shown in Table B-1 was determined over a multiyear period in North American climes, where the mean outdoor temperature averaged 63 °F. Such findings are consistent with metabolic pathways involving sensible and insensible perspiration. As such, the skin absorption/desorption pathways can become an important part of body metabolic throughput of normal water.

Lifestyles also have significant potential influence on the variation of biological half-lives. In one case, for example, the biological half-life of tritium in an adult male was followed for approximately 4 months following an acute exposure, during which time the half-life appeared to fluctuate back and forth between 4 and 10 days at regular intervals. Closer scrutiny revealed that the subject was a weekend jogger. As a result, the appearance of two very different biological half-lives was totally valid.

Variations in biological half-lives have also been shown to be inversely correlated with age. In these cases, however, the data suggest that age correlations introduce variations in the biological half-life of no more than ± 20 percent. When compared to reduction factors of 50 to 250 percent produced by total fluid throughput and/or skin temperature correlations, age correlations are a secondary correction.

B.1.5.2 Multi-Compartment Modeling

For single-compartment modeling, the half-life of interest is that for HTO in the body water. Although it has been observed that the half-life can vary by more than a factor of 2 for the same person, the HTO component of the biological half-life can be expected to be about 10 days. As was noted in Section B.1.3, however, prolonged exposures can be expected to show signs of two additional components that range from 21 to 30 days and 250 to 550 days, respectively. The former reflects the existence of a labile organic pool; the latter suggests the existence of a more tightly bound organic pool.

For purposes of dose calculations, however, the overall contribution from organically bound tritium has been found to be relatively small, i.e., less than about 5 percent. The ICRP methods for computing the annual limits on intake in air and water utilize the body-water component only, including the assumption of a 10-day biological half-life (ICRP, 1979).

B.2 Bioassay and Internal Dosimetry

Exposure to tritium oxide (HTO) is by far the most important type of tritium exposure, and it results in the distribution of HTO throughout the body's soft tissue. The HTO enters the body by inhalation or skin absorption. When immersed in airborne HTO, intake through the lungs is approximately twice that absorbed through the skin. The average biological half-life of tritium is 10 days, but it can vary naturally by 50 percent or more and is dependent on the body-water turnover rate. This has been verified by calculation and by actual measurements of tritium concentrations in body water following exposure. Following exposure to HT, the gas is taken into the lungs and, according to the laws of partial pressures, some is dissolved in the blood stream, which distributes the HT to the body water.

When a person is exposed to HT in the air, two kinds of exposures actually result: one to the lungs and one to the whole body. According to ICRP-30, the lung exposure is the critical one, resulting in an effective dose 25,000 times less than would result from an equal exposure to HTO (for workers doing light work).² However, during exposure to HT, a small fraction of the tritium in the blood is transferred to the gastrointestinal tract, where it is rapidly oxidized by enzymes in the gut. This results in a buildup of HTO, which remains in the body (with its usual half-life), while the HT is rapidly eliminated following the end of the exposure. The resultant dose from the exposure to this HTO is roughly comparable to the effective dose from the lung exposure to HT. Thus, for both HTO and HT exposures, a bioassay program that samples body water for HTO is an essential element of a good personnel-monitoring program for tritium.

B.2.1 Sampling Schedule and Technique

Following an exposure to HTO, it is quickly distributed throughout the blood system and, within 1 to 2 hours, throughout the extra- and intra-cellular volumes and the remaining body water. Once equilibrium is thus established, the tritium concentration is found to be the same in samples of blood, sputum, and urine. For bioassay purposes, urine is normally used for determining tritium concentrations in body water.

Workers potentially or casually exposed to tritium are normally required to submit urine samples for bioassay on a periodic basis. The sampling period may be daily to biweekly or longer, depending on the potential for significant exposure. Usually, the period is weekly to biweekly.

Following an incident, or a work assignment with a higher potential for exposure, a special urine sample is usually required for each individual involved. The preferred method is to wait about 2 to 4 hours for the equilibrium to be established. The bladder is then voided. A sample submitted soon thereafter should be reasonably representative of the body-water concentration.

² As was noted at the beginning of this section, the bulk of the information presented in this section was originally published in 1991. Since that time, more up-to-date dose, and dose assessment, models have been developed. See, for example, the references in Section B.9, "Suggested Additional Reading: (i) the U.S. Environmental Protection Agency's Federal Guidance Report No. 13, and (ii) Peterson and Davis, "Tritium Doses from Chronic Atmospheric Releases: A New Approach Proposed for Regulatory Compliance," both of which were published in 2002.

A sample collected before equilibrium is established will not be representative because of dilution in the bladder or because the initial concentration in the blood will be higher than an equilibrium value. However, any early sample may still be useful as an indication of the potential seriousness of the exposure.

At the bioassay laboratory, 1 milliliter (ml) of the urine is typically mixed with 10 to 15 ml of a suitable scintillation cocktail and counted in a liquid scintillation counter. At many laboratories, the urine is initially counted raw, and if the concentration is above a certain value (e.g., 0.1 microcurie per liter ($\mu\text{Ci/l}$)), the urine is distilled or spiked with a standard and recounted. The counting efficiency may be affected by quenching, although this can be corrected electronically.

The dose equivalent rate in the body water can be calculated directly from the concentration of HTO in body water, which, until recently, was considered to be equivalent to the dose rate to the critical organ. ICRP-30 states that the average dose to the soft tissue could be taken to be equal to the effective dose equivalent. This change effectively dilutes the tritium, and thereby lowers the dose rate accordingly.

From this discussion, the dose equivalent rate, $R(t_0)$, to the soft tissue (63 kg), from a urine concentration of C_0 can be calculated as shown in Equation B.3:

$$\begin{aligned} R(t_0) &= C_0 \left(\frac{\mu\text{Ci}}{l} \right) \times 3.7 \times 10^4 \left(\frac{\text{Bq}}{\mu\text{Ci}} \right) \times 5.7 \times 10^3 \left(\frac{\text{eV}}{\text{Bq}} \right) \times 8.64 \times 10^4 \left(\frac{\text{sec}}{\text{day}} \right) \\ &\quad \times \frac{42 l}{6.3 \times 10^4 \text{ grams}} \times 1.6 \times 10^{-12} \frac{\text{erg}}{\text{eV}} \times 10^{-2} \frac{\text{rad-gram}}{\text{erg}} \times 1.0 \frac{\text{rem}}{\text{rad}} \\ &= 1.94 \times 10^{-4} C_0 \frac{\text{rem}}{\text{day}}. \end{aligned} \quad (\text{B.3})$$

From the dose rate $R(t)$, the committed dose (D_∞) can be calculated from Equation B.4:

$$D_\infty = \int_0^\infty R(t) dt. \quad (\text{B.4})$$

Following a bioassay measurement, the quantity $R(t)$ can be estimated from an assumed biological half-life. A previously measured value (for that individual) or the average value (for reference man) of 10 days may be used. In that case, Equation B.4 becomes Equation B.5:

$$\begin{aligned} D_\infty &= R(t_0) \int_0^\infty e^{-\lambda t} dt = R(t_0) \int_0^\infty e^{-0.693t/T_{\text{Bio}}} dt \\ &= \frac{R(t_0)}{0.693}, \end{aligned} \quad (\text{B.5})$$

where, D_∞ is the committed dose equivalent, $R(t_0)$ is the daily dose rate at $t = t_0$, λ is the elimination constant, and T_{Bio} is the biological half-life in days. However, if a more precise calculation of the individual's dose is required, the actual biological half-life should be determined from the values of subsequent bioassay data.

For very low exposures (<1 to 10 $\mu\text{Ci/l}$), no great error is incurred by assuming a constant half-life between weekly sampling points. For higher exposures, a greater sampling frequency is recommended to determine the dose more accurately.

As was noted above, a pure HT exposure can be thought of as a combination of a lung exposure from the HT and a whole-body exposure from the HTO converted from the HT dissolved in the blood. The whole-body dose can be determined as outlined above by analysis for HTO in the urine. Since the effective dose equivalents from the lung and whole-body exposures are approximately equal, the total effective dose can be conservatively obtained by multiplying the HTO whole-body dose by 2.

In general, this is too conservative (by the factor of 2) because a release of pure tritium gas with <0.01 percent HTO is highly unlikely. With only a slight fraction (~1 percent) of HTO in the air, the effective dose is essentially the HTO whole-body dose as determined by bioassay.

In any exposure to HTO, a certain small fraction of the tritium will exchange with nonlabile organic hydrogen in the body, there to remain until metabolism or exchange eliminates the tritium. Following a high acute or any chronic exposure, two- and three-component elimination curves have been observed (ranging from 30 to 230 days). Although most of the dose is due to the HTO in all of these observed cases, such exposures should be followed until urine concentrations are down to the range of <0.1 to 1 $\mu\text{Ci/l}$, in order to calculate the dose more precisely.

It has also been observed that skin contact with metal surfaces contaminated with T_2 or HT produces tritium-labeled molecules in the skin (possibly catalyzed by the metal), which in turn results in longer elimination times for the labeled or metabolized constituents. Lung exposure to airborne metal tritides may also cause unusual patterns of tritium concentrations in body water, due, supposedly, to retention of these particulates in the lung with subsequent leaching and conversion to organically bound tritium. For these and other reasons, it is good practice to follow the elimination data carefully, and to look for organically bound tritium in the urine.

B.2.2 Dose Reduction

As was noted above, the committed dose following an HTO exposure is directly proportional to the biological half-life, which in turn is inversely proportional to the body-water turnover rate. This rate varies from individual to individual. As may be expected, such things as temperature, humidity, work, and drinking habits may cause rate variations. Although the average biological half-life is 10 days, it can be decreased by simply increasing fluid throughput, especially of liquids that are diuretic in nature (e.g., coffee, tea, beer). The half-life may then be easily reduced to 4 to 5 days; however, a physician should be consulted before any individual is placed on a regimen that might affect his or her health. It is essential that medical supervision be involved if diuretics are taken because the resultant loss of potassium and other electrolytes can be very serious if it is not replaced. Such drastic measures may result in a decrease in half-life to 1 to 2 days. Even more drastic is the use of peritoneal dialysis or a kidney dialysis machine. These may reduce the half-life to 13 and 4 hours, respectively. Such techniques are extreme and should be used only in life-threatening situations, involving potential committed dose equivalents that would exceed a few hundred rem without such treatment.

Individuals whose urine concentrations exceed established limits should be relieved from work involving possible further exposure to radiation, whether from tritium or other sources. Limits are generally suggested or imposed by the health physics organization to make certain that the

annual worker dose limits are not exceeded. The operating group may impose even stricter limits on their staff than those imposed by the health physics group. The actual values, which may range from 5 to 100 $\mu\text{Ci/l}$, are often dependent on the availability of replacement personnel and the importance of the work that needs to be accomplished.

Results of bioassay sampling should be given to workers who submit samples as soon as they are available. The results may be posted, or the workers may be personally notified. Moreover, the results are required to be kept in the workers' personal radiation exposure records or medical files. Like any other radiation exposure, any dose in excess of the regulatory limits must be reported to the appropriate authorities.

B.3 Measurement Techniques

Because an extensive review of tritium measurement techniques is beyond the scope of this document, it will be assumed that the reader is already acquainted with the fundamentals of radiation-detection instruments. However, for those not familiar, an extensive review of tritium measurement techniques can be found in National Council on Radiation Protection and Measurements (NCRP) Report No. 47 (NCRP, 1976). Moreover, a review of site-specific measurement techniques can also be found in the U.S. Atomic Energy Commission's (AEC's) WASH-1269, "Tritium Control Technology" (AEC, 1973). The bulk of the following has been adapted from both sources. Since both documents were published in the 1970s, it can be expected that some of the information will be dated, although the basic measurement techniques have changed very little since that time.³

This section discusses instruments or techniques used for monitoring tritium for health and safety purposes. However, since process-monitoring instruments often involve the same or similar detectors, they are also included in the discussion.

B.3.1 Air Monitoring

Ionization chamber instruments are the most widely used instruments for the measurement of tritium in gaseous (and vapor) forms in laboratory, environmental, and process monitoring applications. Such simple, economical devices require only an electrically polarized ionization chamber, suitable electronics, and, in most cases, a method for moving the gas sample through the chamber, which is usually a pump. Chamber volumes typically range from a tenth to a few tens of liters, depending on the required sensitivity. The output is generally given in units of concentration (multiples of $\mu\text{Ci/m}^3$ or becquerels per cubic meter), or, if a commercial electrometer or pico-ammeter is used, in current units, which must then be converted to concentration. A rule of thumb that can be used to convert current to concentration is concentration ($\mu\text{Ci/m}^3$) = $10^{15} \times$ current (amps)/chamber volume (liters). For real-time tritium monitoring purposes, the practical lower limits of sensitivity range from 0.1 to 10 $\mu\text{Ci/m}^3$.

For measurements of low concentrations, sensitive electrometers are needed. For higher concentrations (e.g., >1 millicuries per cubic meter (mCi/m^3)), the requirements on the electronics can be relaxed, and smaller ion chambers may be used. Smaller chambers also need less applied voltage, but because of a greater surface-area-to-volume ratio, there is a

³ For more recent information on the measurement techniques used at various DOE sites, see also the references cited in Section B.9, "Suggested Additional Reading: (i) "Primer on Tritium Safe Handling Practices," DOE-HDBK-1079-94, December 1994; (ii) "Radiological Training for Tritium Facilities," DOE-HDBK-1105-2002 Chg Notice 2, May 2007; and (iii) "Tritium Handling and Safe Storage," DOE-HDBK-1129-2015, September 2015.

greater likelihood for residual contamination in the chamber, which elevates the background. Response times for higher level measurements can be made correspondingly shorter. However, small chambers and chambers operated at low pressures may have significant wall effects so that the above rule of thumb may not apply. Such instruments would have to be calibrated to determine their response.

Although most ionization chambers are of the flow-through type that require a pump to provide the flow, there are presently a number of facilities that use so-called "open window" or "perforated wall" chambers. These chambers, which may employ a dust cover to protect the chamber from dust and other particulates, allow the air or gas to penetrate through the wall to the inside chamber. Such instruments are currently being used as single-point monitors at several facilities for room, hood, glove box, and duct monitoring.

B.3.2 Differential Monitoring

Because of the greater toxicity of HTO compared to HT (25,000 times greater according to ICRP-30), it is often desirable to know the relative amounts of each species following a release into a room, or release to the environment. In the case of stack monitoring, this is more easily accomplished by taking discrete samples of the stack effluent using bubblers or desiccants in conjunction with a catalyst for oxidizing the HT (see Section B.3.3). For differential monitoring, the simplest technique is to use a desiccant cartridge in the sampling line of an air monitor. The result is a measurement of the HT concentration. Without the cartridge, the total tritium concentration is measured. Subtraction of HT from the total produces the HTO concentration. The technique may be used manually with one instrument or automatically by switching a desiccant cartridge in and out of the sampling line.

Another technique involves the use of a semipermeable membrane tube bundle in the sampling line to remove the HTO (preferentially over the HT), which is then directed to an HTO monitor. After removing the remaining HTO with another membrane dryer, the sampled air is directed to the HT monitor. Although this technique is slower than the one requiring a desiccant cartridge (response and equilibrium times being 1 to 2 minutes and 10 to 20 minutes, respectively), it does not require a periodic cartridge replacement. Furthermore, it can be adapted to the measurement of tritium in both species in the presence of noble gases or other radioactive gases by adding a catalyst after the HTO dryers, followed by additional membrane dryers for the HTO converted from the HT by the catalyst.

B.3.3 Discrete Sampling

Discrete sampling differs from real-time monitoring in that the sampled gas (usually air) must be analyzed for tritium content by means of liquid scintillation counting (in the case of HTO). The usual technique is to flow the sampled air through either a solid desiccant (molecular sieve, silica gel, Drierite™) or water or glycol bubblers. For low-flow rates (approximately 0.1 to 11/min), bubblers may be used. Bubblers are more convenient for sampling but are less sensitive than the solid desiccant technique.

Glycol or water may be used, but glycol is generally preferred for long-term sampling. In any case, the collected water is then analyzed for HTO. For differential monitoring of HTO and HT, a heated catalyst (usually a palladium sponge) is used between the HTO desiccant cartridge or bubblers and the HT cartridge or bubblers. In a different arrangement, palladium is coated on the molecular sieve in the HT cartridge to oxidize and absorb the resulting HTO. This technique, however, is usually only employed for environmental monitoring.

Another technique for sampling HTO in air is to use a “cold finger” to freeze HTO out of the air; an alcohol and dry ice mixture in a stainless-steel beaker works well. To arrive at the concentration, knowledge of the relative humidity is needed. A soft plastic bottle squeezed several times to introduce the air (containing the HTO) into the bottle is another method. A measured quantity of water is then introduced, and the bottle is capped and shaken. In a minute or less, essentially all the HTO is taken up by the water, which is then analyzed.

Other techniques involve placing a number of vials or other small, specially designed containers of water, liquid scintillation counting cocktail, or other liquid in selected locations in the area being monitored. After a period of time (usually a number of days) the liquid in the containers is analyzed. The result is semiquantitative (for open containers) to quantitative (for specially designed containers).

B.3.4 Process Monitoring

Ionization chambers are typically used for stack, room, hood, glove box, and process monitoring. The outputs can be used to sound alarms, activate ventilation valves, turn on detritiation systems, and for other functions. In general, it can be expected that stack, room, and hood monitors will require little nonelectronic maintenance (i.e., chamber replacement due to contamination) because under routine circumstances, the chambers are constantly flushed with clean air and are not exposed to high tritium concentrations for extended periods of time. Glove box monitors, however, can be expected to eventually become contaminated, especially if exposed to high concentrations of HTO. Process control monitor backgrounds can also be expected to present problems if a wide range of concentrations (e.g., four to five orders of magnitude) are to be measured.

Mass spectrometers, gas chromatographs, and calorimeters are generally used as workhorse instruments for process monitoring. Because of their relative insensitivities, however, these instruments cannot be used for the detection of tritium much below a few parts per million (curies per cubic meter). For this reason, care must be taken in the interpretation of analytical results and the related health physics concerns. It is not uncommon, for example, to find that samples that show no trace of tritium when analyzed on a mass spectrometer actually contain several curies of tritium.

B.3.5 Surface Monitoring

In general, it is not possible to measure the total tritium contamination on a surface except by destructive techniques. Even a slight penetration by tritium, for example, becomes quickly undetectable because of the weak energy of its beta particles. With open-window probes operated in the Geiger-Mueller or proportional regions, it is possible to measure many of the particles emitted from the surface. However, quantifying that measurement in terms of the total tritium present is difficult because every exposure history is different, and the relative amounts of measurable to immeasurable tritium are consequently different. Such monitoring probes are then routinely used to measure the accessible part of the contaminating tritium. Care must be taken to protect the probe from contamination. When monitoring a slightly contaminated surface after monitoring a highly contaminated one, contamination of the probe can be an immediate problem. Placing a disposable mask over the front face of the probe can reduce but never eliminate this contamination completely, particularly when the tritium is rapidly outgassing from the surface being monitored.

For highly contaminated surfaces (>1 mCi/100 cm²) it is possible to use a thin sodium iodide crystal or a thin-window GM tube to measure the characteristic and continuous x-rays (bremsstrahlung) emitted from the surface, as a result of the interaction of the beta particle with the surface material. In terms of total surface tritium, such measurements are semiquantitative at best.

B.3.6 Liquid Monitoring

Liquid monitoring is almost universally done by liquid scintillation counting. For liquids other than water, care must be taken that the liquid is compatible with the counting cocktail. Certain chemicals can degrade the cocktail. Others are not miscible and may retain much of the tritium; still others result in a high degree of quenching. In addition, samples that contain peroxide, or that are alkaline, may result in chemiluminescence, which can interfere with the measurement. Such samples should first be neutralized before counting. Chemiluminescence and phosphorescence both decay with time, so that keeping the samples in darkness for a period of hours can usually eliminate the problem. Distillations may be necessary for some samples; use of quenching curves or a special cocktail may be necessary for others.

For rather "hot" samples, as may be the case for vacuum pump oils, bremsstrahlung counting may be useful. This technique may also be useful for active monitoring of "hot" liquids. Active monitoring of liquids may also be done with scintillation flow cells, which are often made of a plastic scintillator material, or of glass tubing filled with anthracene crystals. However, these flow cells are particularly prone to contamination by algae or other foreign material, which can quickly degrade their counting efficiency.

B.4 Instrument Types and Calibration

Instruments used for monitoring tritium in air and on surfaces and for counting tritium samples are discussed in this section. Methods and sources for calibrating such instruments are also discussed. All instruments used for monitoring tritium for health and safety reasons should be calibrated regularly. The calibration frequency is typically 6 months for portable or other instruments receiving hard use, 12 months for fixed instruments, and 12 months or longer for simple instruments such as stack samplers.

B.4.1 Air Monitors

Ionization chambers that are used for air monitoring are described in Section B.3.1. The techniques used to calibrate ion chamber instruments can vary, but traditionally they are calibrated with tritium gas if it is practical to do so. If an instrument (or an instrument system) is calibrated with tritium gas once, then it is generally not necessary to repeat that type of calibration. Thereafter, an electronic calibration from the front end of the electrometer preamplifier (if accessible) made with a calibrated current source (or calibrated resistor and calibrated voltage source) can be used. This is followed by a determination that there is adequate voltage on the chamber, and that the chamber is connected. The latter is verified by use of an external gamma source. Finally, if the chamber is of the flow-through type, proper flow must be verified.

Gas-flow proportional counters are not commonly used for air monitoring in the United States, although there has been some renewed interest in them in recent years. This type of instrument is common in West Germany, where regulations require monitoring at very low levels. Advantages are enhanced sensitivity (approximately 0.01 picocuries per cubic meter) and the

ability to discriminate against background radiation. Disadvantages include (i) increased cost and complexity, (ii) the need for a carrier-counting gas, (iii) low flow rate resulting in slower instrument response, and (iv) limited range (up to approximately 1 mCi/m³). Gas-flow proportional counters are particularly attractive as stack monitors, where increased sensitivity is desirable, and a slower response time is not a problem.

Liquid and plastic scintillation detectors have been developed in Canada and elsewhere to monitor for HTO in air but apparently are not widely used for this purpose. The liquid scintillation counting technique is expensive because it requires a continuous supply of counting cocktail. The plastic scintillator technique, although not very sensitive, has some advantages with regard to size of the detector, which generally consists of two parallel plates of the plastic scintillator arranged in a flow cell. The scintillator, which is relatively insensitive to penetrating gamma rays, can be easily shielded from outside interference because of its small size. For instruments such as gas-flow proportional counters or scintillation counters, use of tritium gas for routine calibration purposes is probably more justified because of the nature of the detectors. This technique particularly applies to scintillation detectors because other techniques are not as effective in determining if the scintillation detectors are working properly.

B.4.2 Surface Monitors

Section B.3.5 describes count rate instruments equipped with windowless gas-flow proportional probes, thin sodium iodide crystals, or thin-window GM tubes that are used to monitor surfaces. Tritiated polystyrene sources can be used to calibrate survey instruments for surface monitoring. Sources are constructed of thin plastic disks for which the tritium beta emission rate from the surface can be determined and certified. The tritium counting efficiency of gas-flow proportional counters under ideal conditions can approach 50 percent. However, normal conditions (e.g., dirty or porous surfaces) can reduce the counting efficiency to 10 percent or less. More stable sources of nickel-63 can also be used to verify the operation of surface-monitoring instruments. However, determination of the tritium counting efficiency cannot be simulated with nickel-63.

B.4.3 Tritium Sample Counters

There are primarily two types of instruments for analyzing tritium samples for radiation-protection purposes: gas-flow proportional counters and liquid scintillation spectrometers.

Gas-flow proportional counters are commercially available with and without a window over the counting chamber and with and without a sample changer mechanism. Windowless counters should be used for tritium samples to obtain the maximum counting efficiency. When a large number of samples can be counted, a proportional counter with an automatic sample changer is recommended. When a number of samples need to be counted quickly, several proportional counters with single-sample capacity may be used to obtain prompt results.

Tritiated polystyrene sources can be used to calibrate proportional counters for analysis of tritium samples. The tritium counting efficiency for 2π proportional counters can approach 50 percent under ideal conditions. However, when dirty smear papers or thick porous samples are counted, the counting efficiency may be reduced to 10 percent or less. More stable nickel-63 sources can also be used to verify the operation of proportional counters.

Detection with liquid scintillation counters has become established as the most convenient and practical way of measuring tritium in the liquid phase. Liquid scintillation counters are

commercially available, many with capabilities for handling several hundred samples. The technique consists of dissolving or dispersing the tritiated compound in a liquid scintillator, subsequently detecting the light emitted from the scintillator, and counting the number of emissions. Major efforts in developing the technique have been directed to improving the detection efficiency of the photo-multipliers, distinguishing the tritium scintillation events from others, and in finding scintillator/solvent mixtures that can accommodate large volumes of sample (especially aqueous samples) without the degradation of the scintillation properties.

Liquid scintillation counters should be calibrated regularly by means of National Institute of Standards and Technology (NIST)-traceable standards. Quenching standards, often supplied by the manufacturer, may be used to establish the counting efficiency for tritium as a function of quenching ratio. The quenching ratio, and hence the counting efficiency, for individual samples can be determined routinely. The tritium counting efficiency for unquenched samples is usually about 35 percent to 50 percent.

B.5 Contamination Control and Protective Measures

Contamination control can be an effective method of limiting uptake of tritium by workers. In this section, smear surveys and off-gassing measurements are described as the primary methods of monitoring the effectiveness of contamination control. For situations where tritium contamination cannot be prevented, a number of protective measures are described that provide engineering controls over the spread of tritium contamination. Respiratory protection, gloves, and other protective clothing for working in tritium-contaminated environments are also described in this section.

B.5.1 Methods of Contamination Control

Any material exposed to tritium or a tritiated compound has the potential of being contaminated. Although it is difficult to quantify tritium contamination levels, there are several methods available to evaluate the existence and relative extent of contamination, including smear surveys and off-gassing measurements. Good housekeeping and work practices are essential in maintaining contamination at acceptable levels within a tritium facility.

The total amount of tritium surface contamination is not an indication of its health or safety implications. Rather, the loose, removable tritium is a more important indicator; this is the tritium that can be transferred to the body by skin contact, or that may outgas and become airborne. Loose contamination is routinely monitored by smears (or swipes), which are wiped over a surface and then analyzed for tritium content by liquid scintillation or proportional counting.

B.5.1.1 Smear Surveys

Surface monitoring by smear counting is an important part of the monitoring program at a tritium facility. It is used to control contamination, to minimize uptake by personnel, and to prevent, or minimize, its spread to less contaminated areas. A routine surface contamination-monitoring program is required, and additional special monitoring should be provided when the condition or situation is warranted.

An effective tritium health physics program must also specify the frequency of routine smear surveys. Based on operating experience and potential contamination, each facility should develop a routine surveillance program that includes daily smear surveys in areas such as

lunchrooms, step-off pads, and change rooms. In other locations within a facility, it may be sufficient to perform weekly or monthly routine smear surveys. In addition to the routine survey program, special surveys should be made on material being moved from one level of control to a lesser-controlled area. This will help prevent the spread of contamination from controlled areas.

Smears are typically small round filter papers used dry or wet (with water, glycol, or glycerol). Wet smears are more efficient in removing tritium and the results are more reproducible, although the papers are usually more fragile when wet. However, tritium smear results are only semiquantitative, and reproducibility within a factor of 2 agreement (for wet or dry smears) is considered satisfactory. Ordinarily, an area of 100 square centimeters of the surface is wiped with the smear paper and quickly placed in a liquid scintillation counting vial with about 10 ml of cocktail, or 1 or 2 ml of water with the cocktail added later. It is important to place the swipe paper in liquid quickly after swiping because losses by evaporation can be considerable, especially if the paper is dry. The counting efficiency is not much affected by the presence of a small swipe.

Foam smears are also commercially available. These dissolve in most cocktails and do not significantly interfere with the normal counting efficiency. Alternatively, the smear paper may be counted by gas-flow proportional counting but, because of the inherent counting delays, tritium losses prior to counting can be significant.

Moreover, counting efficiencies may be difficult to determine and can be expected to vary greatly from one sample to the next. Another drawback is potential contamination of the counting chamber when counting very "hot" smears. For all of these reasons, liquid scintillation counting is the preferred smear-counting system.

B.5.1.1.1 Allowable Tritium Surface Contamination Levels—Background

In the traditional sense, the NRC has not had to deal with tritium contamination, and/or with allowable tritium surface-contamination levels, as these historically have come under the purview of DOE and its predecessor agencies (i.e., the Energy Research and Development Agency (ERDA) and, prior to ERDA, the AEC). It is interesting to note, however, that the subject of allowable tritium surface-contamination levels had fallen through the regulatory cracks for years, because, in spite of the existing ICRP dose models for allowable surface contamination limits for most other radionuclides, the ICRP models contained a disclaimer: "These data are not applicable to pure beta-emitters with a maximum energy equal to, or less than, 150 keV." As a consequence, allowable surface contamination limits for tritium, and carbon-14, simply did not exist.

Some of that began to change in 1977, when the ICRP published its latest recommendations for the safe handling of radioisotopes in hospitals and medical establishments (ICRP, 1977). In their publication of ICRP-25, the ICRP was suggesting a general purpose working limit of 1 nCi/cm² for allowable radionuclide contamination on surfaces. For tritium and carbon-14, however, ICRP-25 specifically noted that the 1 nCi/cm² recommendation could be increased by a factor of 100. Using the appropriate scaling factors, the ICRP-25 recommendations, therefore, were suggesting that the maximum limit for tritium and carbon-14 contamination control levels for controlled area usage should be on the order of 10 μCi/100 cm², or 2.22×10⁷ dpm/100 cm².

In one of the earliest attempts to address the problem for unrestricted use, the State of California, as an Agreement State, adopted an interim set of tritium and carbon-14 surface contamination limits in 1977 (Honey, 1977), based on the existing guidance provided in the AEC's Regulatory Guide 1.86 (AEC, 1974) (this guidance has since been replaced through the License Termination Rule). For the most part, the limits went unquestioned, and, over the years, the same set of limits was adopted by DOE's San Francisco Operations Office (DOE, 1987). Thus, for DOE, the allowable surface contamination limits for removable tritium were set at 10,000 dpm/100 cm².

Everything went reasonably well until 1989, when DOE published its final version of DOE Order 5480.11 (DOE, 1988). Like the AEC had done with its table of "Acceptable Surface Contamination Levels" in Regulatory Guide 1.86, DOE had also published a comparable table of surface radioactivity guides, in a simplified format, in DOE Order 5480.11.

However, it is important to note with respect to the DOE's first version of the Order that DOE did not include a separate category for tritium (or carbon-14). As a consequence, the DOE tritium community found that its regulatory limits for allowable surface contamination limits had been unexpectedly, and arbitrarily, reduced by an order of magnitude. (Tritium was now considered as falling into a generic category, along with β - γ emitters and nuclides with decay modes other than alpha-emission or spontaneous fission.)

When the tritium community objected *en masse*, on both a national and international basis, DOE established the Tritium Surface Contamination Limits Committee to look into and correct the problem. Although the Tritium Surface Contamination Limits Committee came back with recommendations that were more on the order of 100,000 dpm/100 cm² for removable tritium surface contamination, DOE elected to adopt a more conservative limit of 10,000 dpm/100 cm² (Surface Contamination Limits Committee (1991) and 10 CFR Part 835, "Occupational Radiation Protection," respectively.) It is particularly important to note, however, that, while DOE has used the value of 10,000 dpm/100 cm² for the free release of tritium-contaminated items from controlled areas, the surface contamination limits used by DOE are intended primarily for use in occupational exposure situations, and *not* for the free release of tritium-contaminated items to uncontrolled areas.

B.5.1.1.2 Allowable Tritium Surface Contamination Levels—Facility Issues

Because they have not had to deal with the issue in the past, there is no obvious reason to expect the NRC to have any current limits in place to establish action levels operating facilities should use (e.g., nuclear reactors) for tritium surface contamination limits for occupational exposures, nor should it be expected to have limits in place to address the subject of the free release of tritium-contaminated items to uncontrolled areas. As a starting point, therefore, the adoption of the original recommendations of the Tritium Surface Contamination Limits Committee (i.e., 100,000 dpm/100 cm² for operational limits in controlled areas and 10,000 dpm/100 cm² for the free release of tritium-contaminated items to uncontrolled areas) would be appropriate. From an operational standpoint, experience has shown that both values can be used without placing undue administrative burdens on the staff. More importantly, from a health and safety standpoint, the information contained in the Committee's report (Surface Contamination Limits Committee, 1991) has shown that both values are extremely conservative, for both the workers and the general public.

B.5.1.1.3 Allowable Tritium Surface Contamination Levels—Transportation Issues

Although the U.S. Department of Transportation has no specific limits in place to address allowable *tritium* surface contamination, the requirements in 49 CFR 173.443(a) do address allowable surface contamination limits on the external surfaces of *all* radioactive material transportation packages. The basic limit specified for all radionuclides is that the allowable surface contamination limits, for nonfixed (removable) contamination, must be kept as low as reasonably achievable (ALARA). The limits further specify that the allowable surface-contamination limits, for nonfixed (removable) contamination, for β - γ emitters, is 4 becquerels per square centimeter, 1×10^{-4} microcuries per square centimeter, or 220 dpm/cm², all of which translate, in more conventional units, to 22,000 dpm/100 cm². Given the background information noted above in Section B.5.1.1.1, such a value is well in keeping with tritium operations issues and expectations.

The allowable surface contamination limits on the internal surfaces of transportation packages are addressed in 49 CFR 173.428(d), which states that, for an *empty* package, the internal surface contamination levels must not exceed 100 times the limits specified in 49 CFR 173.443(a), or 2.2×10^6 DPM/100 cm². For the shipment of irradiated TPBARs, such a value becomes problematic in that once a package has been used for the shipment of irradiated TPBARs, it can probably never again be shipped as an *empty* package.

B.5.1.2 Out-Gassing Measurements

Basic out-gassing measurements can be made using any of several different methods. The most reliable methods, however, involve the use of a closed-loop system of known volume, and a flow-through ionization chamber monitor. By placing the material inside the volume and by measuring the change in concentration over a period of time, accurate determinations of tritium off-gassing rates can be made on virtually any material. The initial out-gassing rate measured is the required value, since the equilibrium concentration may be quickly reached in a closed volume, especially if the volume is small. Relative health hazards can be determined in absolute terms and, where appropriate, decisions can be made regarding the release of such materials to uncontrolled areas.

B.5.2 Protection Against Airborne Contaminants

Several important engineering controls are available for tritium protection. For the protection of personnel against potential inhalation hazards from tritium, the most commonly used methods include differential pressure zoning, dilution ventilation, and local exhaust ventilation techniques. Depending on the relative hazard, however, additional measures must be considered. In order of increasing protection factors, these might include but are not limited to air-supplied respirators (self-contained breathing apparatus), air-supplied suits, and glove boxes.

B.5.2.1 Differential Room Pressure Zones

Differential room pressure zones are used in virtually all tritium facilities. In general, this technique establishes a natural flow path that leads from less to more hazardous areas. Used in conjunction with dilution ventilation and local exhaust ventilation techniques (see Sections B.5.2.2 and B.5.2.4, below), differential zoning is an important line of defense against the migration of tritium into areas where it is not wanted.

Typical pressure zoning controls should be arranged as follows:

- Using outside air pressure as the reference, office areas and other uncontrolled areas will generally be held between zero (0.00) differential and -0.01 inch of water column.
- Main access corridors outside of the radioactive materials area (RMA) will generally be held between -0.01 inch and -0.025 inch; main access corridors inside the RMA will generally be held between -0.01 inch and -0.05 inch.
- Individual rooms within the RMA will generally be held between -0.1 and -0.15 inch.
- Working arrangements for glove boxes will typically range from -0.25 inch to -1.0 inch, depending on the comfort level of the operators.

In special cases, the pressure differentials may differ from those in the above example.

B.5.2.2 Dilution Ventilation

Dilution ventilation is the once-through flow technique of exchanging outside air for inside air for purposes of comfort and basic contamination control. For comfort control, this technique typically uses cooled air in the summer and warm air in the winter. However, dilution ventilation techniques are inherently inefficient for saving on energy. For contamination control purposes, dilution ventilation techniques are made even more inefficient because large quantities of air are occasionally required for the adequate dilution of room air releases in relatively short time frames.

B.5.2.3 Room Air Exchange

Room air exchange rates in most working environments are typically set to about four air changes per hour. At most tritium facilities, however, exchange rates are routinely set to 10 air changes per hour in RMAs and four to six air changes per hour in offices and other noncontrolled areas. Thus, depending on the size of the facility, it can be expected that the total air throughput for any given tritium facility will be approximately 10^6 to 10^8 cubic meters per day, or higher. Because of increased energy costs in recent years, studies have been conducted at a number of sites in which the feasibility of retrofitting air-handling systems with computerized flow control systems has been examined. The newer systems would automatically cut back on airflow rates during nonpeak periods, and/or when facilities are unoccupied. Although few systems have actually been installed and tested, the impact of such systems should be such that health physics programs will not be affected.

It is important for health physicists to know room air exchange rates to determine waiting times before re-entering a room after tritium releases. Assuming that air change rates are 10 volume changes per hour, the formula shown in Equation B.6 may be used to determine room tritium activity:

$$\text{Final Value} = \text{Initial Value} \times e^{-10t} \quad (\text{B.6})$$

where t is the total time in hours after the release. The initial value of tritium air activity is assumed to have reached equilibrium.

B.5.2.4 Local Exhaust Ventilation

The primary advantages of local exhaust ventilation techniques, effective in tritium facilities, relate to the complete capture of the contaminant, regardless of its evolution rate, relative toxicity, or physical state. In addition, these techniques use relatively low air volumes compared to dilution ventilation. Potential disadvantages of local exhaust ventilation techniques are their relatively complex system design and that, once most systems are installed, they cannot easily be moved to other locations.

B.5.2.4.1 Fume Hoods

Fume hoods are often used in local exhaust ventilation systems. In theory, linear flow established at or near hood openings (face velocities) captures the contaminants and draws them through the hood and into the connecting ductwork. The capture of gases and vapors will generally require lower face velocities than those needed for the capture of particulates. Large and intermediate-sized particles, for example, will sometimes be difficult to capture because of their inherent mass and the forces of gravity. Smaller particles, on the other hand, (below a few microns in size), can be expected to behave in a manner similar to that for gases and vapors.

For tritium work in a fume hood, face velocities in the range of 100 to 150 linear feet per minute (lfpm) are used. Higher velocities (e.g., 150 to 200 lfpm) can produce turbulent flow, resulting in eddy currents that can sweep tritium back to the operator. Since the problem can be further compounded by the location of equipment within the hood, operations involving the use of fume hoods should be periodically reviewed to ensure that adequate protection is being provided.

B.5.2.4.2 Canopy Hoods

Canopy hoods are used in place of fume hoods for housing large equipment. Designed for specific applications, canopy hoods are used at many tritium facilities for the following reasons: (i) to enclose glove box pass-through-port operations, (ii) to house many experiments that are too large to fit into a fume hood, and (iii) in some applications, to house tritium gas-pumping systems.

Canopy hoods, although used with either natural- or forced-air exhaust, are most effective for hot- and warm-air processes where rising thermal currents help pull air into the hood. For tritium work, canopy hoods are usually designed such that heat-producing equipment (e.g., pumps) can be placed at floor level. Hood door openings, which usually slide to the right and to the left, must be designed so that they can function without interfering with the worker or the operation. However, because the protection afforded by canopy hoods can quickly be lost when cross drafts are introduced, hood openings must be kept to a practical minimum whenever the hood is in use.

B.5.2.4.3 Recovery/Cleanup Systems

It is common in many facilities with glove box operations to clean up the air and remove or recover the tritium from the air prior to exhausting to the atmosphere. Various stripper systems and recovery units are used for this purpose. Since environmental concerns are increasing, it is important to maintain environmental releases ALARA.

B.5.2.5 Respirators

In general, respirators that are effective for tritium fall into two categories: air-purifying respirators and air-supplied respirators. Air-purifying respirators usually contain chemical cartridges, special filters, or both, which remove contaminants from air prior to breathing. Air-supplied respirators are of two types: (i) the self-contained type, for which a cylinder of air (or oxygen) or an oxygen-generating chemical provides the necessary oxygen for breathing, or (ii) the hose type, for which air is supplied from an external source. Although ANSI Z88.2 (ANSI, 2015) describes in detail the types of respiratory protection devices that are appropriate for various types of chemical and radiological hazards, the primary use of respirators in a tritium facility is to provide protection against the possible inhalation of HTO. To be effective against HTO, however, respirators must be of the type to remove HTO from air, exchange it for normal water vapor, or be supplied with an external source of clean air.

B.5.2.6 Air-Supplied Suits

Because of the inherent disadvantages normally associated with respirators and other breathing apparatus, air-supplied plastic suits that completely enclose the body are widely used by facilities that process tritium. Prior to using air-supplied suits at DOE facilities, however, the suits must be tested and approved by a DOE Respirator Advisory Committee (RAC) (Bradley, 1984).

The main objectives of air-supplied suits are to (i) provide a layer of circulating air between the worker and the suit, (ii) provide an adequate supply of breathing air for the worker, and (iii) maintain an adequate flow of air from the interior of the suit to the exterior to help keep the body cool. The incoming air must meet the criteria of Type 1, Grade D, breathing air, as specified in the Compressed Gas Association standard for compressed air for human respiration (Compressed Gas Association 2014). The air-supply system should be designed to ensure a high degree of reliability.

Capacity requirements for air-supply systems will be dependent on flow requirements for specific suit designs. There are a wide range of flow rates used in RAC-approved suits (from 6 to 20 cubic feet per minute per suit), and it is not uncommon to have several workers on a manifold system at the same time. Therefore, system capacities should be designed to provide adequate flow to each suit user. Capacities in excess of several hundred cubic feet per minute may be needed per system.

For tritium work, air-supplied suits must be constructed of materials that have acceptable permeation protection against HTO. They must also provide appreciable tear and abrasion resistance. Because they are intended for use in many different environments, suits must be designed to provide adequate vision, to minimize interference with normal work movements, and to be put on and taken off easily. Noise levels in suits resulting from the flow of incoming air must be maintained at levels less than Occupational Safety and Health Administration workplace standards, and they must comply with RAC criteria. Because of the closed environment, and because of the additional background noise caused by the flow of air into the suits, communication methods between personnel may require special equipment.

B.5.2.7 Temporary Enclosures

A more effective way to contain tritium may be to construct a tent (temporary canopy hood or a temporary glove box). The primary difference between the two is that hoods generally exhaust

to the stack and glove boxes generally exhaust to cleanup systems. For tritium, tents can be thought of as being the nominal equivalent of a reactor-type contamination control point when large pieces of equipment or entire areas must be worked on.

Structural members for tents can literally be anything. Smaller glove-bag operations, for example, recommend the use of Tinker-Toys® for support. For larger operations, polyvinyl chloride (PVC) pipe, scaffolding supports, and standard off-the-shelf fittings can be used, along with anything else that is available. Tent walls are usually made of 3-, 6-, or 12-mil fire-retardant PVC plastic sheeting, depending on strength requirements that may develop because of the facility's differential pressures.

Tenting operations are usually designed to allow personnel to work inside. In most cases, personnel working inside will wear air-supplied plastic suits. For these reasons, communication links between personnel inside and outside become vital. Moreover, because many tenting operations involve the use of welding, brazing, grinding, and/or other hot processes, additional emphasis must be placed on possible fire hazards.

B.5.3 Protection Against Non-Airborne Contaminants

The personnel protective equipment worn by workers is one of the most important aspects of an effective health physics program. Since tritium can be easily absorbed through the skin or through inhalation, personnel protective equipment must protect against both exposure routes. The following describes protective measures and equipment that may be used for skin-absorption pathways.

B.5.3.1 Gloves, General

In some operations, the hands and forearms of workers can be exposed to high tritium concentrations in many forms, and the proper selection of gloves and glove materials is essential.

Many factors should be considered in selecting the proper type of glove. Factors to be considered in making the selection include chemical compatibility, permeation resistance, abrasion resistance, solvent resistance, glove thickness, glove toughness, glove color, shelf life, and unit cost. Gloves are commercially available in materials such as butyl rubber, natural rubber, neoprene rubber, neoprene and natural rubber blends, nitrile (Buna-N®), and PVC plastics, polyvinyl alcohol (PVA) coated fabrics, and Viton®.

Table B-2 shows the chemical compatibility of eight of the available glove materials, along with recommended and nonrecommended uses. The data clearly indicate that certain types of materials are not recommended for use with certain types of chemicals. Different types of gloves should be readily available for use in routine handling of chemicals.

Table B-3 lists some of the physical properties of commercially available gloves that can be found in common use at most facilities. Listed in order of their cost, prices can be expected to range from well under \$1 per pair for the thinnest (0.005 inch thickness) PVC gloves to more than \$30 per pair for Viton® (0.012 inch thickness).⁴ Also included in Table B-3 are additional

⁴ Price estimates listed are in 1980 dollar estimates.

Table B-2 Chemical Compatibility of Available Liquid-Proof Gloves

Material	Recommended for:	Not recommended for:
Butyl	Dilute acids and alkalis, ketonic solvents, gas and vapor permeation protection	Petroleum oils, distillates, and solvents
Natural rubber	Ketonic solvents, alcohols, photographic solutions	Petroleum oils, distillates, and solvents
Neoprene	Concentrated nonoxidizing acids and concentrated alkalis	Halogenated or ketonic solvents
Neoprene/natural blends	Dilute acids and alkalis, detergents, and photographic solutions	Halogenated or rubber ketonic solvents
Nitrile	Petroleum-based solvents, distillates, and oils	Halogenated or ketonic solvents
PVC	General purpose, low-risk hand protection	Halogenated or ketonic solvents
PVA	Halogenated solvents, paint shop applications	Water or water-based solutions
Viton®	Halogenated solvents, concentrated oxidizing acids	Aldehydes, ketonic solvents

Table B-3 Physical Properties of Commercially Available Gloves

Glove material	Length (in.)	Thickness (in.)	Shelf life	Relative toughness	HTO permeation
PVC	11	0.005	Fair	Fair	Poor
PVC	11	0.010	Good	Good	Fair
PVC	11	0.020	Excellent	Excellent	Good
Neoprene/natural rubber blend	14	0.020	Good	Good	Good
Neoprene	11	0.015	Excellent	Good	Good
Neoprene	18	0.022	Excellent	Good	Good
Natural rubber	11	0.015	Poor	Fair	Good
Nitrile	13	0.015	Excellent	Excellent	Good
Nitrile	18	0.022	Excellent	Excellent	Good
Butyl	11	0.012	Excellent	Poor	Excellent
PVA ^a	12	0.022	Good	Excellent	Poor
Viton®	11	0.012	Excellent	Excellent	Excellent

^a As a coated, flock-lined fabric, the thickness of PVA gloves can vary by as much as ± 20 percent. Because the PVA coating is water soluble, other properties of PVA gloves can also be expected to vary, depending on their long-term exposure to moisture.

considerations for glove length, as well as comparisons of shelf life, glove toughness, and HTO permeation characteristics. The rating system for the data in Table B-3 is as follows. Under

“Shelf life,” “Excellent” refers to an indefinite time span with no obvious loss of properties; “Poor” refers to a time span of between 6 and 12 months, the loss of basic properties being obvious; “Fair” and “Good” refer to arbitrary time spans of 2 and 4 years, respectively, with some loss of properties becoming evident over time. “Relative toughness” is a combined heading based on inherent glove properties reinforced by thickness where appropriate. The data suggest, for example, that the overall rating for nitrile gloves should not change appreciably with increasing thickness because toughness is a property inherent in the glove. For PVC gloves, however, the ratings do change with thickness because the relative toughness of PVC gloves is primarily a function of the cross-sectional area of the glove-body wall. The ratings for protection against HTO permeation are listed relative to butyl and Viton® gloves, both of which are rated as “Excellent.” For all these ratings, it is assumed that the gloves will be discarded before steady-state permeation of HTO (HTO breakthrough) can occur. In all cases, these ratings are dependent on the total thickness of the glove (i.e., the cross-sectional area of the glove-body wall).

Additional gloves that might be considered are polyethylene gloves (11 × 0.00175 inches) and surgeon’s gloves (11 × 0.006 inches). Other properties that might be considered include the availability of powdered versus nonpowdered gloves. The former are important when dexterity is needed; the latter are better suited for high-vacuum and ultra-high-vacuum work.

The use of two or more glove layers should be considered for complex chemical operations, such as waste treatment and handling, and also for maintenance operations that might include the potential for exposure to a wide variety of chemical compounds, such as plumbing replacement operations on large-scale vacuum effluent capture systems that have been in tritium service for several years. Although basic protection schemes can be determined for most combinations of chemical species, the best gloves are composed of three layers of liquid-proof gloves and an underlying layer of absorbent glove material (i.e., a cotton glove liner). Different-colored layers for indicating which layers fail to meet protection requirements should also be considered. This further means of protection would prove beneficial for most workers, except for the small percentage of workers who are colorblind.

B.5.3.2 Lab Coats and Coveralls

Lab coats and coveralls (fabric barriers) are worn at various times in almost all tritium facilities. Lab coats are normally worn for the general protection of street clothes as part of the daily routine. For added protection, coveralls are sometimes worn instead of a lab coat when the work is unusually dusty, dirty, or greasy. However, in most cases, the protection afforded by lab coats and coveralls is little more than cosmetic.

Unless they are treated with water-resistant or waterproofing agents, open-weave fabrics, such as those normally associated with lab coats and coveralls, provide minimal barriers against the airborne diffusion of HTO. Moreover, it can be expected that the HTO protection that is afforded will be the result of straightforward mechanical factors: some of the HTO will become absorbed in the weave of the fabric, some will be trapped in air pockets between layers of fabrics, and some will be trapped in air pockets that separate the fabric layers from the skin. Perspiration levels near the skin surface, both sensible and insensible, can be expected to add an additional short-term dilution factor. For the most part, however, it can be expected that, unless lab coats and/or coveralls are changed often, approximately every 10 minutes or so, diffusion and dilution effects will quickly reach equilibrium in high HTO concentration operations, and all barrier effects will be nullified.

Waterproof and water-resistant lab coats and coveralls have been tested at various laboratories. In most cases, however, they are not recommended for everyday use because of the excessive heat loads inflicted on the worker. Many facilities prefer the use of open-weave fabrics for lab coats and coveralls and the use of an approved laundry for contaminated clothing. Other facilities have opted instead to use disposable paper lab coats and coveralls, exchanging the costs associated with a laundry for the costs associated with replacement and waste disposal.

B.5.3.3 Shoe Covers

Although shoe covers can provide protection factors that range over several orders of magnitude, the routine use of shoe covers in a tritium facility must be thoroughly weighed against actual need. Like lab coats and coveralls, shoe covers offer little protection against spreadable particulates and/or gases and vapors. As a general rule, shoe covers are not recommended for the control of spreadable contamination, except in highly contaminated areas, because good housekeeping (i.e., regular dusting, washing, and waxing of floors) provides better control over contamination spread. For localized contamination problems, such as those that might result from spills of tritium-contaminated liquids and solids, the use of liquid-proof shoe covers should be considered to prevent the spread of contamination.

B.6 Decontamination

Methods available for decontaminating materials are based on material composition and the extent of tritium contamination. Effective decontaminating agents include soap and water, detergents, bleach, alcohol, and Freon™. Since decontamination is often difficult, especially where surfaces are exposed to high concentrations of tritium for extended periods, tools and specialized equipment routinely used in process areas should be stored there for reuse.

Action levels should be established for the different tritium facility control zones to ensure that tritium contamination levels do not build up over time. For example, smearable limits for uncontrolled material release and clean areas at different facilities may range from 1,000 to 10,000 dpm/100 cm². Smearable limits in controlled zones may be much higher, but an effective health physics program should have procedural limits on the amount of smearable contamination permitted. When these action levels are exceeded, timely decontamination efforts should be initiated.

In spite of all the precautions normally taken, there may be occasional tritium contamination of workers. Effective personal decontamination methods include rinsing of the affected part of the body with cool water and soap. If the entire body is affected, a shower should be taken using soap and water as cool as can be tolerated. This will help keep the skin pores from opening, thus minimizing skin absorption.

B.7 Maintenance

Maintenance activities and operations sometimes require work to be done on equipment outside of a hood or glovebox environment. Several techniques are available for this type of operation, such as close-capture methods and contaminant huts or tents. Taking advantage of localized crosscurrents, “snorkels” and “elephant trunks” used as flexible exhaust lines can be placed directly over or adjacent to the work to be performed. Face velocities of several thousand lfpm can be generated to aid in keeping off-gassing tritium away from the workers. (See Section B.5.2, above).

B.8 References

10 CFR Part 835, "Occupational Radiation Protection", Appendix D, "Surface Contamination Values."

American National Standards Institute, "American National Standard for Respiratory Protection," ANSI Z88.2, 2015.

Bradley, O.D., "Acceptance-Testing Procedures for Air-Line Supplied Suits," LA-10156, Los Alamos National Laboratory, 1984.

Compressed Gas Association, "Compressed Air for Human Respiration," CGA-G7.1, New York, NY, 2014.

Honey, D.D., "State of California Inspection Policy Memorandum #8, Revised Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use," June 30, 1977.

International Commission on Radiological Protection, *The Handling, Storage, Use and Disposal of Unsealed Radionuclides in Hospitals and Medical Research Establishments*, ICRP Publication 25, Ann. ICRP 1 (2), Pergamon Press, Oxford, 1977. See, in particular, Section 9, paragraphs 175–177, pp. 27–28.

ICRP, *Limits for Intakes of Radionuclides by Workers*, ICRP Publication 30 (Part I and Supplements), Ann. ICRP 2 (3-4), Pergamon Press, New York, NY, 1979.

National Council on Radiation Protection and Measurements, "Tritium Measurement Techniques," NCRP Report No. 47, Washington, DC, 1976.

Surface Contamination Limits Committee Report, "Recommended Tritium Surface Contamination Release Guides," February 1991.

U.S. Atomic Energy Commission, Tritium Control Technology, edited by T.B. Rhinehammer and P.H. Lamberger, Monsanto Research Corporation Report, WASH-1269, Miamisburg, OH, 1973.

U.S. Atomic Energy Commission, "Termination of Operating Licenses for Nuclear Reactors," Regulatory Guide 1.86, June 1974.

U.S. Department of Energy, San Francisco Operations Office, "Requirements for Radiation Protection," Management Directive SAN MD 5480.IA, CH. XI, Section 8, paragraph (g), Attachment I, June 15, 1987.

U.S. Department of Energy, "Radiation Protection for Occupational Workers," DOE Order 5480.11, December 21, 1988.

U.S. Department of Energy, "Health Physics Manual of Good Practices for Tritium Facilities," MLM-3719, December 1991.

B.9 Suggested Additional Reading

Peterson, S-R., and P.A. Davis, "Tritium Doses from Chronic Atmospheric Releases: A New Approach Proposed for Regulatory Compliance," *Health Physics*, 82(2): pp. 213–225, 2002.

U.S. Department of Energy, "Primer on Tritium Safe Handling Practices," DOE-HDBK-1079-94, December 1994.

U.S. Department of Energy, "Radiological Training for Tritium Facilities," DOE-HDBK-1105–2002 Chg Notice 2, May 2007.

U.S. Department of Energy, "Tritium Handling and Safe Storage," DOE-HDBK-1129–2015, September 2015.

U.S. Environmental Protection Agency, "Federal Guidance Report No. 13: CD Supplement," EPA 402-C-99-001, Rev. 1, Oak Ridge National Laboratory, Oak Ridge, TN, 2002.

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11. ABSTRACT (200 words or less)

This standard review plan (SRP) provides guidance to the U.S. Nuclear Regulatory Commission (NRC) staff for reviewing an application for package approval issued under Title 10 of the *Code of Federal Regulations* (10 CFR), Part 71, "Packaging and Transportation of Radioactive Material." NRC approval of a package design typically results in issuance of a certificate of compliance (CoC) or a letter amendment for a transportation package. The objectives of this SRP are to assist the NRC staff in its reviews by:

- providing a basis that promotes uniform quality and a consistent regulatory review of an application for a CoC for a transportation package
- presenting a basis for the review's scope
- identifying acceptable approaches to meeting regulatory requirements
- suggesting possible evaluation findings that can be used in the safety evaluation report

This SRP may be revised and updated as the need arises on a chapter-by-chapter basis to clarify the content, correct errors, or incorporate modifications approved by the Director of the NRC Division of Spent Fuel Management. Comments, suggestions for improvement, and notices of errors or omissions should be sent to and will be considered by the Director, Division of Spent Fuel Management, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001.

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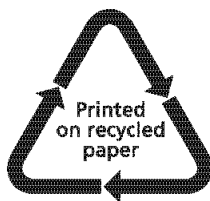
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