*Kirk-Othmer Encyclopedia of Chemical Technology.*

# DEUTERIUM AND TRITIUM, TRITIUM

Tritium [15086-10-9], the name given to the hydrogen isotope of mass 3, has symbol $^3H$ or more commonly T. Its isotopic mass is 3.0160497 (1). Moletecular tritium [10028-17-8], $T_2$, is analogous to the other hydrogen isotopes. The tritium nucleus is energetically unstable and decays radioactively by the emission of a low-energy $\beta$ particle. The half-life is relatively short ($\sim$12 yr), and therefore tritium occurs in nature only in equilibrium with amounts produced by cosmic rays or man-made nuclear devices.

Tritium was first prepared in the Cavendish Laboratory by Rutherford, Oliphant, and Harteck in 1934 (2, 3) by the bombardment of deuterophosphoric acid using fast deuterons. The D–D nuclear reaction produced tritium ($^2D + ^2D \xrightarrow{3} T + ^1H + \text{energy}$), but also produced some $^3He$ by a second reaction ($^2D + ^2D \xrightarrow{3} He + n^1 + \text{energy}$). It was not immediately known which of the two mass-3 isotopes was radioactive. In 1939 it was established (4) that $^3He$ occurred in nature and was stable. Tritium was later proved to be radioactive. A vivid history of the unravelling of the complex relationships between tritium, deuterium, and helium-3 is available (5).

## 1. Physical Properties

Tritium is the subject of various reviews (6–8), and a book (9) provides a comprehensive survey of the preparation, properties, and uses of tritium compounds. Selected physical properties for molecular tritium, $T_2$, are given in Table 1.

Calculated vapor pressure relationships of $T_2$, HT, and DT have been reported (10) (see Deuterium and tritium, deuterium). An equation for the vapor pressure of *solid tritium* in units of kPa, $T$ in Kelvin, has been given (11):

$$\log p = 5.6023 - 88.002/T$$

The three-phase region of $D_2$–DT–$T_2$ has been studied (12). Relative volatilities for the isotopic system deuterium–*deuterium tritide*–tritium have been found (13) to be 5–6% below the values predicted for ideal mixtures.

All components appear miscible in both liquid and solid phases from 17 to 22 K. For a 50–50 mol % mixture of liquid D–T at ca 19.7 K, the gas phase contains ca 42% T and the solid phase 52%.

The T–T bond energy has been estimated at 4.5881 *e*V (14).

The entropy of $T_2$ at 298.15 K is 164.8562 kJ/mol (39.4016 kcal/mol), the specific heat is 29.1997 J/(mol·°C) (6.9789 cal/(mol·°C)), and the Gibbs free energy is 135.9083 kJ/mol (32.4829 kcal/mol). These values were derived from extensive *ab initio* calculations for $T_2$ at spin equilibrium, ortho and para $T_2$, and the isotopomers HT and DT (15).

**Table 1. Physical Properties of Molecular Tritium**[a]

| Property | Value |
|---|---|
| melting point, at 21.6 kPa[b], K | 20.62 |
| boiling point, K | 25.04 |
| critical temperature, K | 40.44[c] |
| critical pressure, MPa[d] | 1.850 |
| critical volume, $cm^3$/mol | 57.1[e] |
| heat of sublimation, J/mol[f] | 1640 |
| heat of vaporization, J/mol[a] | 1390 |
| entropy of vaporization, J/(mol·K)[f] | 54.0 |
| molar density of liquid, mol/L | |
| 20.62 K[b] | 45.35 |
| 25 K | 42.65 |
| 29 K | 39.66 |

[a] Values are from Ref. 11 unless otherwise indicated.
[b] Value represents the triple point (162 mm Hg).
[c] From Ref. 10.
[d] To convert MPa to psi, multiply by 145.
[e] Value is calculated.
[f] To convert J to cal, divide by 4.184.

### 1.1. Ortho-Para Tritium

As in the case of molecular hydrogen, molecular tritium exhibits nuclear spin isomerism. The spin of the tritium nucleus is $\frac{1}{2}$, the same as that for the hydrogen nucleus, and therefore $H_2$ and $T_2$ obey the same nuclear isomeric statistics (16). Below 5 K, molecular tritium is 100% para at equilibrium. At high (100°C) temperatures the equilibrium concentration is 25% para and 75% ortho. The kinetic parameters of conversion for $T_2$ at low temperatures are faster than rates at corresponding temperatures for $H_2$. In the solid phase the conversion of molecular tritium to a state of ortho-para equilibrium is 210 times as fast as that for molecular hydrogen.

The experimental and theoretical aspects of the radiation and self-induced conversion kinetics and equilibria between the ortho and para forms of hydrogen, deuterium, and tritium have been correlated (17). In general, the radiation-induced transitions are faster than the self-induced transitions.

### 1.2. Properties of $T_2O$

Some important physical properties of $T_2O$ are listed in Table 2. Tritium oxide [14940-65-9] can be prepared by catalytic oxidation of $T_2$ or by reduction of copper oxide using tritium gas. $T_2O$, even of low (2–19% T) isotopic abundance, undergoes radiation decomposition to form HT and $O_2$. Decomposition continues, even at 77 K, when the water is frozen. Pure tritiated water irradiates itself at the rate of 10 MGy/d ($10^9$ rad/d). A stationary concentration of tritium peroxide, $T_2O_2$, is always present (9). All of these factors must be taken into account in evaluating the physical constants of a particular sample of $T_2O$.

## 2. Nuclear Properties

### 2.1. Radioactivity

Tritium decays by $\beta$ emission, $^3T \longrightarrow ^3He + \beta^-$. A summary of the radioactive properties of T, adapted from Ref. 22, is given in Table 3.

**Table 2. Physical Properties of $T_2O$**

| Property | Value | Reference |
|---|---|---|
| mol wt | 22.032 | |
| triple point, °C | 4.49 | 18 |
| temperature of maximum density, °C | 13.4 | |
| boiling point, °C | 101.51 | 18 |
| density at 25°C, g/mL | 1.2138 | 19 |
| $\Delta H^{\circ}_{\mathrm{vap}}$ at 25°C, kJ/mol[a] | ca 45.81 | 18 |
| liquid vapor pressure at 25°C, kPa[b] | 2.64 | |
| vibrational fundamentals, $\mathrm{cm}^{-1}$ | 1017, 2438 | 20 |
| ionization constant at 25°C | ca $6 \times 10^{-16}$ | 21 |

[a] To convert J to cal, divide by 4.184.
[b] To convert kPa to mm Hg, multiply by 7.5.

**Table 3. Radioactive Properties of Tritium**

| Property | Value |
|---|---|
| half-life, yr | 12.43[a] |
| decay constant, $\mathrm{s}^{-1}$ | $1.7824 \times 10^{-9}$ |
| mean $\beta$ energy, keV | 5.7 |
| molar activity, TBq/mol[b] | 2128 |

[a] Courtesy of the National Institute of Standards and Technology.
[b] To convert Bq to Ci, divide by $3.7 \times 10^{10}$

### 2.2. Nuclear Fusion Reactions

Tritium reacts with deuterium or protons (at sufficiently high temperatures) to undergo nuclear fusion:

$${}^{3}\mathrm{T} +{}^{2}\mathrm{D} \xrightarrow{4} \mathrm{He} + n^{1} + 17.6\ \mathrm{MeV}$$

$${}^{3}\mathrm{T} +{}^{1}\mathrm{H} \xrightarrow{4} \mathrm{He} + 19.6\ \mathrm{MeV}$$

The first of these nuclear fusion reactions produces a neutron that can be used to form a new atom of tritium as well as evolving a very large amount of energy in the form of extremely hot helium. Nuclear fusion using tritium can be initiated and sustained at the lowest temperature (at least in principle) of any nuclear fusion reaction known. Tritium thus becomes the key element both for controlled thermonuclear energy sources and in the uncontrolled release of thermonuclear energy in the hydrogen bomb (see Fusion energy).

### 2.3. Nuclear Magnetic Resonance

All three hydrogen isotopes have nuclear spins, $I \neq 0$, and consequently can all be used in nmr spectroscopy (Table 4) (see Magnetic spin resonance). Tritium is an even more favorable nucleus for nmr than is ${}^{1}\mathrm{H}$, which is by far the most widely used nucleus in nmr spectroscopy. The radioactivity of T and the ensuing handling

**Table 4. Nuclear Magnetic Resonance Properties of Hydrogen Isotopes**

| Isotope | Nuclear spin | Resonance frequency,[a] MHz | Relative sensitivity[b] | Magnetic moment, $10^{-4}$ J/T[c] |
|---|---|---|---|---|
| H | 1/2 | 100.56 | 1.000 | 25.8995 |
| D | 1 | 15.360 | $9.64 \times 10^{-3}$ | 7.9513 |
| T | 1/2 | 104.68 | 1.21 | 27.625 |

[a] At a field of 2.35 T (23.5 kilogauss).
[b] At constant field.
[c] To convert J/T to $\mu_B$ (nuclear Bohr magnetons), divide by $9.274 \times 10^{-24}$.

problems are a deterrent to widespread use for nmr. Considerable progress has been made in the applications of tritium nmr (23, 24).

## 3. Chemical Properties

Most of the chemical properties of tritium are common to those of the other hydrogen isotopes. However, notable deviations in chemical behavior result from isotope effects and from enhanced reaction kinetics induced by the $\beta$-emission in tritium systems. Isotope exchange between tritium and other hydrogen isotopes is an interesting manifestation of the special chemical properties of tritium.

### 3.1. Isotope Effects

Any difference in the chemical or physical properties of two substances that differ only in isotopic composition constitutes an isotope effect. Isotope effects are usually largest when the isotope is directly involved in the rate-determining step of a reaction. The greater the mass of an atom, the lower its zero-point bond energy, and the greater the activation energy required to cleave a chemical bond. In general, therefore, reactions involving rupture of a $-C-T$ bond may proceed at a markedly slower rate than those involving cleavage of a corresponding $-C-H$ bond. Kinetic isotope effects arising from bond cleavage are termed primary isotope effects. Secondary isotope effects occur as a result of the presence of the isotope in nearby molecular sites. Bonds involving the isotope are neither broken nor formed in the reaction. Secondary isotope effects are generally smaller than primary effects. The latter may easily be 10 to 100 times greater. Solvent isotope effects include many important primary effects, eg, solvolyses and acid-base reactions, as well as secondary effects such as solvation. Although primary and secondary kinetic isotope effects are the most extensively studied, numerous other isotope effects have been observed with tritium. Thus, an H/T separation factor of about 14 occurs in the electrolysis of HOT (25, 26). Other tritium isotope effects of significant magnitude have been observed in ion exchange (qv) (27) and gas chromatography (qv) (28, 29). Many other examples have been described (9).

### 3.2. Enhanced Reaction Kinetics

For reactions involving tritium, the reaction rates are frequently larger than expected because of the ionizing effects of the tritium $\beta$-decay. For example, the uncatalyzed reaction $2\ T_2 + O_2 \longrightarrow 2\ T_2O$ can be observed under conditions (25°C) for which the analogous reaction of $H_2$ or $D_2$ would be too slow for detection (30).

### 3.3. Isotopic Exchange Reactions

Exchange reactions between the isotopes of hydrogen are well known and well substantiated. The equilibrium constants for exchange between the various hydrogen molecular species have been documented (18). Kinetics of the radiation-induced exchange reactions of hydrogen, deuterium, and tritium have been critically and authoritatively reviewed (31). The reaction $T_2 + H_2 \longrightarrow 2HT$ equilibrates at room temperature even without a catalyst (30).

In 1957, it was demonstrated (32) that tritium could be introduced into organic compounds by merely exposing them to tritium gas. Since that time hundreds of compounds, of types as simple as methane and as complex as insulin, have been labeled with tritium by this basic method of isotope exchange. Much work has been done to optimize conditions for the exchange technique through control of operating variables such as temperature, pressure, and addition of noble gases to facilitate energy transfer (33). Exchange of the hydrogen of organic compounds with tritium gas has been facilitated by activating the gas by ultraviolet light, $\gamma$- and x-ray irradiation, and microwave discharge. Although high chemical yields are obtained by the original, ie, Wilzbach, technique, highly tritiated impurities of structures similar to but not identical with that of the starting material are formed by direct irradiation damage of the target material and by decomposition of the tritiated products by self-irradiation. Separation of radioactive impurities produced in Wilzbach labeling may prove difficult, as is the task of proving that the radioactive T introduced into the substrate compound is actually in the compound of interest.

Catalytic exchange in solution between an organic compound and tritium gas or $T_2O$ is a general procedure for introducing tritium with high specificity. Much higher molar specific activities (greater than 1.85 GBq/mmol (50 mCi/mmol)) can be attained than with the Wilzbach method. Both homogeneous and heterogeneous catalysts, as well as acid-base catalysis, can be used.

Hot atom reactions have also been used to label organic compounds with T. Irradiation of helium-3 with neutrons according to the nuclear reaction $^3He(n,p)^3H$ produces very energetic tritium atoms that can displace ordinary hydrogen in organic compounds. This procedure is not very selective, and the labeling pattern must be determined to enable the tritiated product to be used effectively as a tracer (34).

## 4. Natural Production and Occurrence

Tritium arises in nature by the action of primary cosmic rays (high-energy protons) or cosmic-ray neutrons on a number of elements. Natural tritium was first detected in the atmosphere (35) and was later shown to be present in rainwater (36). Because of its relatively short radioactive half-life, naturally produced tritium does not accumulate indefinitely and the amount of tritium found in nature is very small. The unit for measurement of natural tritium, the tritium unit (TU) signifies a ratio of 1 atom of tritium per $10^{18}$ atoms of hydrogen. A very excellent worldwide survey of tritium levels in natural waters has been compiled (37). Values range from less than one TU for water in certain deep wells and at extreme sea depths to several hundred TU in samples of rainwater taken during periods of active thermonuclear weapons testing. The level of tritium in atmospheric hydrogen increased from 3800 TU in 1948–1949 to 490,000 TU in 1959 (38).

The principal source of natural tritium is the nuclear reactions induced by cosmic radiation in the upper atmosphere, where fast neutrons, protons, and deuterons collide with components of the stratosphere to produce tritium:

$$^{14}N + n^1 \xrightarrow{3} T + ^{12}C$$

$$^{14}\mathrm{N} + ^{1}\mathrm{H} \xrightarrow{3} \mathrm{T} + \text{fragments}$$

$$^{2}\mathrm{D} + ^{2}\mathrm{D} \xrightarrow{3} \mathrm{T} + ^{1}\mathrm{H}$$

The most important of these reactions by far is the $^{14}\mathrm{N}(n,\ ^{12}\mathrm{C})^{3}\mathrm{T}$ reaction (39). The energetic tritons so produced are incorporated into water molecules by exchange or oxidation, and the tritium reaches the earth's surface as rainwater.

Large-scale detonation of hydrogen bombs in the atmosphere during the 1950s and 1960s, and inadvertent tritium losses have had a permanent impact on the tritium content of the atmosphere. For example, some 20,000 TBq (500,000 Ci) of tritium was released by accident into the atmosphere at Aiken, South Carolina in September, 1984 (40). The deposition of tritium in rainfall (mainly as HTO) is not uniform, and water in different localities can have very different tritium contents. The total deposition of tritium on the continental United States for the period 1953–1983 is estimated (41) at $12 \pm 2$ kg. In the United States, tritium in ground water is smallest in the Southwest, and highest in the Midwest. These differences may be associated with annual rainfall, the introduction of water from the Pacific Ocean, weather patterns, and the like. The transport, dispersion, cycling, and analysis of tritium in the environment receives considerable attention (42) because of the possible large-scale use of tritium in nuclear fusion.

Tritium has also been observed in meteorites and material recovered from satellites (see also Extraterrestrial materials). The tritium activity in meteorites can be reasonably well explained by the interaction of cosmic-ray particles and meteoritic material. The tritium contents of recovered satellite materials have not in general agreed with predictions based on cosmic-ray exposure. For observations higher than those predicted (Discoverer XVII and satellites), a theory of exposure to incident tritium flux in solar flares has been proposed. For observations lower than predicted (Sputnik 4), the suggested explanation is a diffusive loss of tritium during heating up on reentry.

## 5. Production

### 5.1. Nuclear Reactions

The primary reaction for the production of tritium is

$$^{6}\mathrm{Li} + n^{1} \xrightarrow{3} \mathrm{T} + ^{4}\mathrm{He} + 4.78\ \mathrm{MeV}$$

The capture cross section of $^{6}$Li for this reaction using thermal neutrons is $930 \times 10^{-28}\ \mathrm{m}^2$ (930 b) (43). All of the experimental data available to the end of 1986 on the cross sections for the nuclear reaction $^{7}\mathrm{Li} + n \longrightarrow ^{4}\mathrm{He} + n + \mathrm{T} - 2.47\ \mathrm{MeV}$, which utilizes the much more abundant isotope $^{7}$Li, are collected in a review (44).

A second, more favorable reaction is

$$^{3}\mathrm{He} + n^{1} \xrightarrow{3} \mathrm{T} + ^{1}\mathrm{H}$$

for which the capture cross section of $^{3}$He to thermal neutrons is $5200 \times 10^{-28}\ \mathrm{m}^2$ (5200 b). The limited availability of $^{3}$He (0.00013–0.00017% natural abundance) (45) restricts the practical importance of this mode of production (see also Helium-group gases). Tritium is also produced by the action of high energy protons (such as primary cosmic rays) on a number of elements, and by the reaction of cosmic ray neutrons and $^{14}N$. Reaction cross sections are small, generally a few to a few hundred $m^2 \times 10^{-31}$ (millibarns).

### 5.2. Production in Target Elements

Tritium is produced on a large scale by neutron irradiation of $^6Li$. The principal U.S. site of production is the Savannah River plant near Aiken, South Carolina where tritium is produced in large heavy-water moderated, uranium-fueled reactors. The tritium may be produced either as a primary product by placing target elements of Li–Al alloy in the reactor, or as a secondary product by using Li–Al elements as an absorber for control of the neutron flux.

The confinement region in which nuclear fusion proceeds is surrounded by a blanket in which the neutrons produced by the fusion reaction are captured to produce tritium. Because of its favorable cross section for neutron capture, lithium is the favored blanket material. Various lithium blanket materials have been considered, ranging from liquid lithium metal, lithium-lead alloys, or lithium dioxide to aqueous solutions of lithium salts. Lithium ceramics such as lithium aluminate, $LiAlO_2$, and lithium zirconates, $Li_2ZrO_3$, $Li_6Zr_2O_7$, and $Li_8ZrO_6$, continue to show promise as candidate breeder materials (46). Extraction of tritium from the breeder blanket also poses many problems.

### 5.3. Production in Heavy Water Moderator

A small quantity of tritium is produced through neutron capture by deuterium in the heavy water used as moderator in the reactors. The thermal neutron capture cross section for deuterium is extremely small (about $6 \times 10^{-32}$ $m^2$), and consequently the tritium produced in heavy water moderated reactors is generally significant only as a potential health hazard. However, in a high-flux reactor such as that at the Institute Max von Laue-Paul Langevin (Grenoble, France), the heavy water moderator is a useful source of tritium (39).

### 5.4. Production in Fission of Heavy Elements

Tritium is produced as a minor product of nuclear fission (47). The yield of tritium is one to two atoms in 10,000 fissions of natural uranium, enriched uranium, or a mixture of transuranium nuclides (see Actinides and transactinides; Uranium).

### 5.5. Production-Scale Processing

The tritium produced by neutron irradiation of $^6Li$ must be recovered and purified after target elements are discharged from nuclear reactors. The targets contain tritium and $^4He$ as direct products of the nuclear reaction, a small amount of $^3He$ from decay of the tritium and a small amount of other hydrogen isotopes present as surface or metal contaminants.

In the recovery process the gaseous constituents of the target are evolved, and the hydrogen isotopes separated from other components of the gas mixture. A number of methods that can be applied to a process mixture or to naturally occurring sources are available for separating the tritium from the hydrogen and deuterium. Because of the military importance of tritium, details of the large-scale production of this isotope have not been published. A report, however, is available that describes the large-scale production of tritium and its uses in France (48).

### 5.6. Isotopic Concentration

A number of techniques have been reported for concentrating tritium from naturally occurring sources. For example, separation factors (H/T) of 6.6 to 29 were observed (49) for the concentration of tritium by electrolysis of tritiated water. Tritium is concentrated in the undecomposed water.

Low (20–25 K) temperature distillation has been widely used to separate hydrogen and deuterium and has also been successfully applied to the separation of tritium from the other hydrogen isotopes (50, 51). At Los Alamos National Laboratory, a system of four interlinked cryogenic fractionation columns has been designed for the separation of an approximately equal mixture of deuterium and tritium containing a small amount of ordinary hydrogen into a tritium-free stream of HD for waste disposal, and streams of high-purity $D_2$, DT, and $T_2$ (52) (see Cryogenics). Mathematical models that are in good agreement with experimental results on the separation of deuterium–tritium by cryogenic distillation have been developed (53).

Concentration by gas chromatography has also been demonstrated. Elution chromatography has been used on an activated alumina column to resolve the molecular species $H_2$, HT, and $T_2$, thereby indicating a technique for separation or concentration of tritium (54). This method was extended (55) to include deuterium components. The technique was first demonstrated in 1964 using macro quantities of all six hydrogen molecular species (56).

Successful separations of tritium from hydrogen and deuterium have been achieved by a cryogenic thermal diffusion column (57), by diffusion through a palladium–silver–nickel membrane (58), and by chromatography on coated molecular sieves (59). Laser separation of tritium also appears to be competitive with more conventional isotope separation methods (60) (see Lasers). Large separation coefficients have been reported for zirconium chromium hydride ($ZrCr_2H_x$)–hydrogen isotope systems (61). A number of processing options thus are available for processing fuel and product streams containing H, D, and T in nuclear fusion reactors.

## 6. Analysis and Detection

Tritium is readily detectable because of its radioactivity. Under certain conditions concentrations as low as 370 $\mu$Bq/mL ($10^{-8}$ $\mu$Ci/mL) can be detected. Most detection devices and many analytical techniques exploit the ionizing effect of the tritium $\beta$-decay as a principle of operation (62, 63).

### 6.1. Ionization Chamber

The ionization chamber is a simple, sensitive, and sturdy device filled with gas and containing two electrodes between which a potential difference is maintained. When gas containing tritium is admitted to the chamber, the radiation ionizes the gas, the ions are drawn to the electrodes, and a flow of current results that is proportional to the tritium concentration. Because of the ability to detect very small currents, this technique is very sensitive and can be adapted to either static or flow systems. Ionization chambers are used as process-stream monitors, leak detectors, stack monitors, breathing-air monitors, detectors for surface contamination, and detectors instrumented with vibrating-reed electrometers. For the last instrument, concentrations of tritiated water vapor in air of 370 $\mu$Bq/mL ($10^{-8}$ $\mu$Ci/mL) (STP) can be measured. Developments in very low background proportional counters and chambers to be used for low-level internal gas counting of $\beta$-particles emitted by tritium are the subject of a comprehensive review (64). The combination of a proportional counter and a computer significantly enhances the measurement of very low levels of tritium in air.

### 6.2. Mass Spectrometer

The mass spectrometer is the principal analytical tool of direct process control for the estimation of tritium. Gas samples are taken from several process points and analyzed rapidly and continually to ensure proper operation of the system. Mass spectrometry is particularly useful in the detection of diatomic hydrogen species such as HD, HT, and DT. Mass spectrometric detection of helium-3 formed by radioactive decay of tritium is still another way to detect low levels of tritium (65). *Accelerator mass spectroscopy* (*ams*) has also been used for the detection of tritium and carbon-14 at extremely low levels. The principal application of ams as of this writing has been in archeology and the geosciences, but this technique is expected to facilitate the use of tritium in biomedical research, various clinical applications, and in environmental investigations (66).

### 6.3. Thermal-Conductivity Analyzer

The thermal-conductivity analyzer operates on the principle that the loss of heat from a hot wire by gaseous conduction to a surface at a lower temperature varies with the thermal conductivity of the gas, and is virtually independent of pressure between 1.3 kPa (10 mm Hg) and 101 kPa (1 atm). This technique is frequently used in continuous monitors for tritium in binary gas mixtures for immediate detection of process change.

### 6.4. Calorimeter

The $\beta$-decay energy of tritium is very precisely known (9). The thermal energy generated by the decay can thus be used with a specially designed calorimeter to measure the quantity of tritium in a system of known heat capacity.

### 6.5. Liquid Scintillation Counter

The rapid and sensitive technique of liquid scintillation counting is applied for the determination of tritium in liquid systems. The tritiated sample is dissolved in a solvent that contains an organic scintillator. Because many samples, particularly those of a biological nature, are not soluble in water or organic solvents, emulsions are usually used in scintillation counting (67, 68). The accurate determination of tritium in biosystems is a particularly difficult problem because of the sizeable isotope effect encountered in the removal of tissue water. Methods for minimizing tritium fractionation during water removal have been described (69).

The emitted $\beta$ particles excite the organic molecules which, in returning to normal energy levels, emit light pulses that are detected by a photomultiplier tube, amplified, and electronically counted. Liquid scintillation counting is by far the most widely used technique in tritium tracer studies and has superseded most other analytical techniques for general use (70).

### 6.6. Analysis of H–D–T Mixtures

Raman spectroscopy is a very useful and practical method for the analysis of diatomic molecules containing tritium and deuterium or hydrogen. Absolute light scattering intensities for the rotational Raman lines can be predicted, thus making absolute analyses possible. Gas chromatography is another excellent method for the analysis of H–D–T mixtures. The stationary phase consists of alumina, $Al_2O_3$, coated with ferric oxide, $Fe_2O_3$; neon is used as the carrier gas. Detectors are usually both thermal conductivity (caratherometer) and ion chamber detectors.

## 7. Health Physics Aspects

### 7.1. Hazards

Because tritium decays with emission of low-energy radiation ($E_{\mathrm{av}} = 5.7\ \mathrm{keV}$), it does not constitute an external radiation hazard. However, tritium presents a serious hazard through ingestion and subsequent exposure of vital body tissue to internal radiation. The body assimilates tritiated water and distributes it throughout body fluids with remarkable speed and efficiency. When exposed to tritiated water vapor via inhalation, people absorb 98–99% of the activity inspired through the respiratory system (71). Uniform distribution throughout body fluids occurs within 90 minutes. Also, when exposed to such an atmosphere, tritium entering the body through the total skin area approximately equals that entering the lungs. Molecular or elemental tritium ($T_2$) or HT is much less readily assimilated. Approximately 0.004% of such activity inspired is absorbed, apparently after preliminary oxidation in the lungs. Negligible amounts of elemental tritium are absorbed through the skin.

It is generally assumed that ingested tritiated water is rapidly absorbed and uniformly distributed in the body fluids, with the result that the entire organism is uniformly irradiated. This may not necessarily be the case. In experiments using mice, the ingestion of low-level tritiated water causes liver damage (72). The ingestion of tritium used as a tracer in organic molecules that are metabolized in specific pathways can concentrate tritium, resulting in the possibility of localized radiation damage. For example, tritiated thymidine concentrates selectively in the DNA of cells, resulting in selective damage to cell nuclei (73). Environmental assessments of tritium must take these factors into consideration (74).

The body excretes tritium with a biological half-life of 8–14 d (10.5 d average) (75), which can be reduced significantly with forced fluid intake. For humans, the estimated maximum permissible total body burden is 37 MBq (1 mCi). The median lethal dose ($LD_{50}$) of tritium assimilated by the body is estimated to be 370 GBq (10 Ci). Higher doses can be tolerated with forced fluid intake to reduce the biological half-life.

### 7.2. Monitoring and Control

Detailed descriptions of methods used for handling and monitoring tritium at Savannah River (76, 77) and the European Tritium Handling Program (78) have been published.

A widely used instrument for air monitoring is a type of ionization chamber called a Kanné chamber. Surface contamination is normally detected by means of smears, which are simply disks of filter paper wiped over the suspected surface and counted in a windowless proportional-flow counter. Uptake of tritium by personnel is most effectively monitored by urinalyses normally made by liquid scintillation counting on a routine or special basis. Environmental monitoring includes surveillance for tritium content of samples of air, rainwater, river water, and milk.

The radiological hazard of tritium to operating personnel and the general population is controlled by limiting the rates of exposure and release of material. Maximum permissible concentrations (MPC) of radionuclides were specified in 1959 by the International Commission on Radiological Protection (79). For purposes of control all tritium is assumed to be tritiated water, the most readily assimilated form. The MPC of tritium in breathing air (continuous exposure for 40 h/wk) is specified as 185 kBq/mL (5 $\mu$Ci/mL) and the MPC for tritium in drinking water is set at 3.7 GBq/mL (0.1 Ci/mL) (79). The maximum permitted body burden is 37 MBq (one millicurie). Whenever bioassay indicates this value has been exceeded, the individual is withdrawn from further work with tritium until the level of tritium is reduced.

Personnel are protected in working with tritium primarily by containment of all active material. Containment devices such as process lines and storage media are normally placed in well-ventilated secondary enclosures (hoods or process rooms). The ventilating air is monitored and released through tall stacks; environmental tritium is limited to safe levels by atmospheric dilution of the stack effluent. Tritium can be efficiently removed from air streams by catalytic oxidation followed by water adsorption on a microporous solid absorbent (80) (see Absorption).

Several new technologies are in the process of development at the Savannah River plant that would considerably enhance safety in handling large amounts of tritium. Metal hydride technology has been developed to store, purify, pump, and compress hydrogen isotopes. Conversion to or extraction from metal triteride would offer flexibility and size advantages compared to conventional processing methods that use gas tanks and mechanical compressors, and should considerably reduce the risk of tritium gas leaks (see Hydrides).

Personnel who must work in areas in which tritium contamination exceeds permitted levels are safeguarded by protective clothing, such as ventilated plastic suits. Detailed descriptions of laboratories suitable for manipulation of tritium can be found in Reference 9.

## 8. Uses

Nuclear fusion is an approach to the ever increasing global demands for energy. All nuclear fusion reactions require very high temperatures for initiation. The thermal threshold is lowest for light ions, and the nuclear reaction $D(T,n)^4He$, involving the fusion of deuterium and tritium nuclei is considered to be the most practical approach to the realization of nuclear fusion energy (qv). Whereas the technology for large-scale production of deuterium exists, the production and handling of tritium is one of the key problems in the achievement of practical nuclear fusion.

The development of a tritium fuel cycle for fusion reactors is likely to be the focus of tritium chemical research into the twenty-first century.

Tritium is widely used as a tracer in molecular biology (see Radioactive tracers).

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## Related Articles

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