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Standard Guide for Understanding Cyanide Species¹

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1. Scope*

1.1 This guide defines guidance based on a consensus of viewpoints for interpretation of test results to identify various chemical forms of cyanide. It is intended to provide a general understanding of the chemical nature of distinct cyanide species as related to chemical analysis and environmental fate and transport.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 ASTM Standards:²

D1129 Terminology Relating to Water

D1426 Test Methods for Ammonia Nitrogen In Water

D3590 Test Methods for Total Kjeldahl Nitrogen in Water

D6888 Test Method for Available Cyanides with Ligand Displacement and Flow Injection Analysis (FIA) Utilizing Gas Diffusion Separation and Amperometric Detection

D7237 Test Method for Free Cyanide and Aquatic Free Cyanide with Flow Injection Analysis (FIA) Utilizing Gas Diffusion Separation and Amperometric Detection

3. Terminology

3.1 *Definitions*—For a definition of terms used in this guide, refer to Terminology **D1129**.

4. Significance and Use

4.1 This guide provides standard terminology for use in identifying and describing the different chemical forms of cyanide. The complex nature of cyanide chemistry, existence of numerous distinct chemical forms as well as the various regulatory distinctions that may be made can lead to confusion in technical discussions on cyanide and in the selection of

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

appropriate methods for its analysis. This guide is intended to provide clarification and a common framework of terms and definitions to facilitate discussions and referencing different cyanide chemical species and groups of cyanide compounds.

4.2 The use of such common terminology is particularly important from an environmental perspective because certain forms of cyanide are considered to be toxic. Therefore, their release into the environment is regulated by federal and state agencies. Thus a general understanding of cyanide chemistry and species definitions is needed for proper wastewater management and testing.

5. Cyanide Species Terms and Definitions

5.1 Chemistry Related Terms and Definitions:

5.1.1 *Cyanide Ion*—The term used to describe a negatively charged ion comprised of one carbon atom and one nitrogen atom triply bonded to each other ($C\equiv N^-$). The cyanide ion is reactive and readily forms neutral compounds or anionic complexes with most metals.

5.1.2 *Free Cyanide*—The form of cyanide that is bioavailable and known for its toxic effect on organisms (**1**).³ Free cyanide refers to the sum of molecular hydrogen cyanide (HCN) and cyanide ion (CN^-). Hydrogen cyanide is a colorless, poisonous gas having an odor of bitter almonds (mp = $-13.4^\circ C$, bp = $25.6^\circ C$). It is readily soluble in water existing as HCN or CN^- , or both, depending on the pH conditions ($pK_a = 9.36$). At a pH of 7 or less in water, free cyanide is present entirely as HCN; the opposite is true at pH 11 or greater. Because of its toxicity, free cyanide is regulated in environmental wastewater discharges.

5.1.2.1 In Test Method **D7237**, sum of the free cyanide (HCN and CN^-) and cyanide bound in the metal-cyanide complexes that are easily dissociated into free cyanide under the test conditions described in Test Method **D7237** at pH 6 and room temperature.

5.1.3 *Aquatic Free Cyanide*—In Test Method **D7237**, free cyanide measured when the buffer or temperature is adjusted to mimic the receiving water environment.

5.1.4 *Simple Cyanide*—A neutral compound comprised of an alkali metal, alkaline earth metal or ammonium cation

³ The boldface numbers in parentheses refer to a list of references at the end of this standard.

*A Summary of Changes section appears at the end of this standard

bound to cyanide. Simple cyanides are so named because of their structural simplicity and their ability to completely dissolve and dissociate in water to produce free cyanide and a cation according to the following reaction:



where:

A = alkali metal, alkaline earth metal or ammonium cation.

Examples of simple cyanides include sodium cyanide (NaCN) and potassium cyanide (KCN).

5.1.5 Metal Cyanide Complex—A negatively charged ionic complex consisting of several cyanide ions bound to a single transition metal cation. Also referred to as “metal-complexed cyanides,” “metal cyano-complexes” or “transition metal cyanides,” these species have the general formula:



where:

M = transition metal cation,

b = number of cyanide groups, and

x = ionic charge of the transition metal complex.

Metal cyanide complexes are represented by the following equilibrium in aqueous solution:



where:

M = transition metal cation,

n = ionic charge of the transition metal cation,

b = number of cyanide ions, and

x = ionic charge of the transition metal complex.

The degree of dissociation of the metal cyanide complex is dependent of the stability of the complex and the solution pH. On this basis, metal cyanide complexes are divided into two categories: (1) “weak acid dissociable metal cyanide complexes” and (2) “strong acid dissociable metal cyanide complexes.”

5.1.5.1 Weak and Dissociable Metal Cyanide Compounds and Complexes—A cyanide compound or complex that either dissociates under conditions of weak acid distillation, pH buffering, or ligand-exchange reagents. Because of their ability to dissociate under slightly acidic or slightly basic to nearly neutral, ambient conditions, or through the use of ligand-exchange reagents, the weak and dissociable metal cyanide compounds and complexes are sometimes regulated along with free cyanide in wastewater discharges. Several weak and dissociable metal cyanide compounds and complexes are presented in Table 1. A weak and dissociable metal cyanide compound or complex is also sometimes referred to as a “weakly complexed cyanide,” “dissociable cyanide,” “available cyanide,” “directly toxic cyanide,” etc.

(1) Weak Acid Dissociable Metal Cyanide Compounds and Complexes—A cyanide compound or complex that dissociates under mildly acidic conditions (pH = 3–6) and in dilute solutions, forming free cyanide. Complex cyanides bound with cadmium, zinc, silver and copper typically dissociate under mildly acidic distillation conditions.

(2) Ligand Exchange Dissociable Metal Cyanide Compounds and Complexes—A cyanide compound or complex that

TABLE 1 Selected Weak Acid Dissociable Metal Cyanide Compounds and Complexes (2)

Metal Cyanide Complex	Stability Constant (log K at 25°C)
[Hg(CN) ₄] ²⁻ ^A	6.22
Hg(CN) ₂ ^B	32.8
[Cd(CN) ₄] ²⁻	17.9
[Zn(CN) ₄] ²⁻	19.6
[Ag(CN) ₂] ⁻	20.5
[Cu(CN) ₄] ³⁻	23.1
[Ni(CN) ₄] ²⁻	30.2

^A Refers to the stepwise dissociation: [Hg(CN)₄]²⁻ ⇌ Hg(CN)₂ + 2CN⁻.

^B Hg(CN)₂ will be recovered by the available cyanide method (5.2.8) provided that ligand-exchange reagents are used.

dissociates under the action of ligand-exchange reagents and gas diffusion conditions (see Test Method D6888). Complex cyanides bound with nickel or mercury typically require ligand-exchange reagents for dissociation.

(3) pH Buffering Dissociable Metal Cyanide Compounds and Complexes—A cyanide compound or complex that dissociates under the action of pH buffering, forming free cyanide (see Test Method D7237). Simple cyanides bound with sodium and complex cyanides bound with zinc or cadmium are amenable to dissociation using pH 6–8 buffer.

5.1.5.2 Strong Metal Cyanide Complex—A metal cyanide complex that requires strongly acidic conditions (pH <2) in order to dissociate and form free cyanide. Due to their resistance to dissociation and subsequent low toxicity, the strong metal cyanide complexes are distinguished on a regulatory basis from other forms of cyanide. Although some of the strong metal cyanide complexes are also subject to photochemical dissociation when exposed to UV radiation, the rate of dissociation is generally low in naturally turbid, shaded surface waters. In addition, volatilization and biodegradation of any dissociated free cyanide typically prevents their accumulation to toxic levels in the environment thus supporting this regulatory distinction. The term “strongly complexed cyanide” is also sometimes used to describe a strong metal cyanide complex. The most prevalent and well known of such species are the iron cyanide complexes namely, ferrocyanide [IUPAC nomenclature: hexacyanoferrate(II) ion] and ferricyanide [IUPAC nomenclature: hexacyanoferrate(III) ion; IUPAC = International Union of Pure and Applied Chemistry] as well as gold and cobalt cyanide complexes. Examples of strong metal cyanide complexes are presented in Table 2.

5.1.6 Metal-Metal Cyanide Complex Salts—Neutral compounds comprised of one or more metal cations and an anionic cyanide complex. The metal cations balance the charge of the anionic complex thus creating a neutral species. These species are divided into two categories: (1) “alkali metal-metal cyanide

TABLE 2 Selected Strong Metal Cyanide Complexes (2, 3)

Cyanide Complex	Stability Constant (log K at 25°C)
[Fe(CN) ₆] ⁴⁻	35.4
[Au(CN) ₂] ⁻	37 ^A
[Fe(CN) ₆] ³⁻	43.6
[Co(CN) ₆] ³⁻	64 ^A

^A This stability constant is considered to be an estimate.

complex salts” or “alkaline earth metal-metal cyanide complex salts” and (2) “transition metal-metal cyanide complex salts”.

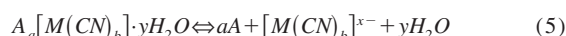
5.1.6.1 *Alkali Metal-Metal Cyanide Complex Salts*—Compounds comprised of one or more alkali metal cations and an anionic cyanide complex having the general formula:



where:

- A = alkali metal counter cation,
- a = number of alkali metal counter cations,
- M = transition metal cation,
- b = number of cyanide ions, and
- y = number of waters of crystallization.

Alkali metal-metal cyanide complex salts readily dissolve in water to form a free alkali metal cation and an anionic metal cyanide complex as follows:



where:

- A = alkali metal counter cation,
- a = number of alkali metal counter cations,
- M = transition metal cation,
- b = number of cyanide ions,
- x = ionic charge of the transition metal complex, and
- y = number of waters of crystallization.

5.1.6.2 *Alkaline Earth Metal-Metal Cyanide Complex Salts*—Structurally and chemically similar to alkali metal-metal cyanide complex salts, these compounds contain an alkaline earth metal cation in place of an alkali metal cation (see 5.1.6.1).

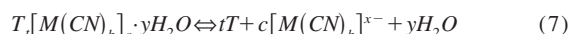
5.1.6.3 *Transition Metal-Metal Cyanide Complex Salts*—Compounds consisting of one or more transition metal cations and an anionic metal cyanide complex having the general formula:



where:

- T = transition metal counter cation,
- t = number of transition metal counter cations,
- M = transition metal cation,
- b = number of cyanide ions,
- c = number of metal complex anions, and
- y = number of waters of crystallization.

Transition metal-metal cyanide complex salts are extremely stable and generally insoluble under acidic and neutral pH conditions (4-7). All transition metal-metal cyanide complex salts, however, are soluble under alkaline conditions. Dissolution into aqueous solution is represented by the following equilibrium:



where:

- T = transition metal counter cation,
- t = number of transition metal counter cations,
- b = number of cyanide ions,
- c = number of metal complex anions,
- x = ionic charge of the transition metal complex, and
- y = number of waters of crystallization.

NOTE 1—Metal cyanide complexes that contain other ligands besides

cyanide may also exist in aqueous solution. Examples of such complexes include: $Hg(OH)CN$ and $[Fe(CN)_5H_2O]^{3-}$ (7).

NOTE 2—When both the transition metal counter cation and metal cation bonded to the cyanide ligands are the same metal, the species is referred to as a double metal cyanide complex salt. An example of a double metal cyanide complex salt is the ferric ferrocyanide species [IUPAC nomenclature: iron (III) hexacyanoferrate (II)] known as prussian blue: $Fe_4[Fe(CN)_6]_3$.

5.2 Operationally Defined Definitions:

5.2.1 *Inorganic Cyanide*—This category includes all inorganic compounds or ionic complexes containing one or more cyanide ligands bonded directly to either a metal or an ammonium ion.

5.2.2 *Organic Cyanide*—Organic compounds containing a cyanide functional group. Examples of naturally occurring organic cyanides are the cyanogenic glycosides. These species are comprised of a cyanide group bound to a carbon atom that is in turn bound by a glycosidic linkage to one or more sugars as depicted in Fig. 1. Specific examples of naturally occurring organic cyanides include linamarin, dhurrin, and amygdalin (Fig. 2). Organic cyanides also include nitriles, which are commercially prepared, substituted hydrocarbons such as acetonitrile (CH_3CN) or cyanobenzene (C_6H_5CN). Because the chemical bond to the cyanide functional group in organic cyanides is very stable, free cyanide is generally not released from organic cyanides in aqueous solution under normal ambient conditions.

5.2.3 *Total Cyanide*—Total cyanide is an analytically defined term that refers to the sum total of all of the inorganic chemical forms of cyanide that dissociate and release free cyanide when refluxed under strongly acidic or alkaline conditions. Total cyanide may also include some organic forms of cyanide that may release free cyanide under the conditions of the analysis. Total cyanide is determined analytically through strong acid distillation or UV irradiation followed by analysis of liberated free cyanide (8-10) on aqueous samples preserved with NaOH. In water, total cyanide includes the following dissolved species: free cyanide, weak acid dissociable metal cyanide complexes and strong metal cyanide complexes. However, it should be noted that because of the sample preservation, certain suspended or colloidal forms of cyanide will dissolve prior to the distillation step; the recovery of which during the acid distillation step is variable and depends on various solution parameters, such as cyanide concentration in suspended solids, ionic strength of the sample, sample temperature, acid digestion times, and so forth. Also, some of the strong metal cyanide complexes, such as those of gold, cobalt and platinum, might not be fully recovered during the total cyanide analytical procedure.

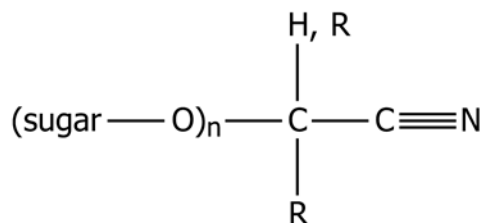


FIG. 1 Cyanogenic Glycoside General Structure