

M. SAMPLING AND ANALYSIS OF SOLUBLE METAL COMPOUNDS

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CONTENTS:	<u>Page</u>
1. Introduction . . . . .	165
2. Soluble and Insoluble Metal Compounds . . . . .	166
3. Health Effects . . . . .	167
4. Sampling Considerations . . . . .	167
5. Analytical Considerations . . . . .	168
6. ISO Procedure for Soluble Metals and Metalloids . . . . .	169
7. Summary . . . . .	171
8. References . . . . .	172
9. Appendix . . . . .	174

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1. INTRODUCTION

Workplace exposure standards have been established for several soluble metals and metalloids to take into account the increased bioavailability of some metal compounds. Exposure standards for soluble compounds can be up to 500 times lower than the exposure standards for less soluble compounds for the same metal. However, there is often confusion among chemists, industrial hygienists, and laboratories over what is meant by “soluble” when the metal species, extraction fluid, or solubility conditions are not specified in the exposure standard nor in the supporting exposure standard documentation [1]. In addition, the metals and metal compounds may interact chemically or physically with the sampling media or with each other. Such complications can affect the stability and speciation of the metals and their compounds, and must be addressed in order to obtain meaningful results. These issues are becoming more important in workplace airborne metals exposure monitoring.

The solubility of a metal will depend on the chemical form of the metal, the fluid used to extract the metal, and the conditions under which the extraction occurs (e.g., temperature, volume, time). Unfortunately, the degree of method specificity needed to obtain measurements that are reproducible among laboratories is generally either missing or is subject to a variety of interpretations from exposure standards and supporting documentation. The need for a better definition of what is meant by the term “soluble” in relation to exposure standards was first raised in 1994, but to date no significant improvement has occurred within United States exposure standard setting organizations. Therefore, to meet the needs of analysts, laboratories, and laboratory clients for better definition of the analyte of interest, and to improve measurement reproducibility among laboratories, various organizations are attempting to achieve international consensus on extraction of soluble metal compounds. New guidelines have been promulgated in an International Standard, [3] and this will serve to fill the void and improve the situation.

## 2. SOLUBLE AND INSOLUBLE METAL COMPOUNDS

The *American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs)* [4] list metals and metalloids having soluble TLVs; updates are published annually. Those from 2002 are listed in Table 1. For most of these elements, the TLVs for the soluble compounds are lower than for the corresponding insoluble forms (Aluminum [Al], Silver [Ag], Hexavalent Chromium [Cr<sup>VI</sup>], Molybdenum [Mo], Nickel [Ni], Platinum [Pt], Rhodium [Rh], Tungsten [W]), while for the remainder (Barium [Ba], Iron [Fe], Thallium [Tl]) the TLVs for soluble and insoluble compounds are the same [3]. Several countries (e.g., France, Germany, UK, USA) have also adopted workplace exposure standards for various soluble metal compounds.

**TABLE 1. METALLIC ELEMENTS FOR WHICH SOLUBLE COMPOUNDS HAVE BEEN ASSIGNED TLVs.<sup>3</sup>**

<b>Element and Soluble Compounds Thereof</b>	<b>TLV, Time-Weighted Average (mg/m<sup>3</sup>)</b>
Aluminum - Soluble salts, as Al	2
Barium - Soluble compounds, as Ba	0.5
Chromium - Water-soluble Cr <sup>VI</sup> compounds	0.05
Iron - Soluble salts, as Fe	1
Molybdenum - Soluble compounds, as Mo	0.5
Nickel - Soluble compounds, as Ni	0.1
Platinum - Soluble salts, as Pt	0.002
Rhodium - Soluble compounds, as Rh	0.01
Silver - Soluble compounds, as Ag	0.01
Thallium - Soluble compounds, as Tl	0.1
Tungsten - Soluble compounds, as W	1
Uranium - Soluble compounds, as U	0.2

Solvent The term “solubility,” as used by analytical chemists, ordinarily pertains to the dissolution of a material in pure water [5]. The subject of water solubility of metal compounds is covered in several references [5-8]. According to *Patty’s Industrial Hygiene and Toxicology* [7] and the individual TLV documentation for these metals [6], the solubilities of metals and metal compounds are quite variable depending upon the solvent. Other pertinent references sustain the notion that solubility, regarding metals and their compounds, is generally identified in terms of their solubility in water [6]. The solubility and insolubility of numerous inorganic substances are presented in the Appendix. What is meant by “soluble” depends on the operational definition employed for the extraction conditions desired by the investigator.

Temperature. Temperature is another variable that directly affects solubility. Most current analytical methods specify deionized water, but not water temperature (some procedures call for hot water (37°C), but others use water at room temperature). Some important questions thus arise:

- a. If using deionized water, should chemists assure that water temperature has been

heated to body temperature (i.e., 37°C)? For TLV purposes, should solubility be based upon body temperature?

- b. Should the TLV documentation specify that analytical procedures use extraction media heated to body temperature?

### 3. HEALTH EFFECTS

From a health perspective, the solubility of a metal or metal compound is not the only consideration of interest. Ultimately, the most important consideration is the extent to which such soluble metals accumulate in body fluids or target organs, leading to toxic levels of the metal ion. This is of more concern than solubility in water, acids, or alkalis per se. Further complicating the solubility issue is the fact that the term “soluble” may have different meanings among industrial hygienists and chemists. Chemists generally use the term “soluble” as defined by the *CRC Handbook of Chemistry and Physics* [5]. According to the *Handbook*, a material is considered soluble if a saturated solution in water (at 25 °C) contains more than 1% (m/v); any material in which 1 percent or less is dissolved is considered insoluble. Unfortunately, a material listed as insoluble, using the CRC definition, could still dissolve in body fluids and produce a significant tissue concentration which is biologically detrimental. The point is that an occupational exposure limit (OEL) for an “insoluble” compound may not be sufficient to protect exposed workers. When asked in an informal poll to choose a solvent in which to measure the relative solubility of metals, industrial hygienists chose, in order of preference, water, body fluids, and a petroleum solvent [1].

Body Fluids. When considering the biological effect of the solubility of a material, we should ideally first consider body fluids. However, body fluids vary considerably in pH. For example, the pH of the stomach is acidic, the pH in the intestine is alkaline, the pH of blood serum is approximately neutral, some macrophages are highly acidic, and the pH of saliva is slightly acidic. Furthermore, body fluids contain a variety of solutes, including salts and polypeptides (proteins). Polypeptide molecules can wrap around metal ions in solution and often contain functional groups that can chelate metals. Polypeptides have strong chelating ability in body fluids and will account for the considerable difference between the solubility of a metal in body fluids versus that same metal in water. Metals, in turn, are bound to different proteins, depending upon where in the body they are located at a given time. In passing through the body, a metal ion is bound by different polypeptides. For each of them, a different reaction may be involved. Some reactions may increase or decrease the toxicity of the metal ion.

Because of the effect of proteins, pH, and other solutes in body fluids, the solubility of a metal compound in body fluids will be quite different than the metal’s solubility in water [9].

### 4. SAMPLING CONSIDERATIONS

Filter Reactivity. The filter medium used must not react with the airborne particulate collected by the sampler so as to change the chemical form of the captured sample. This can occur if a soluble compound reacts with the filter material or a contaminant therein to produce an insoluble or less soluble compound. An example of this problem has been observed with silver, where a soluble silver compound,  $\text{AgNO}_3$ , can react with chloride in some mixed cellulose ester (MCE) or polyvinyl chloride (PVC) filters to form  $\text{AgCl}$ , which is much less

soluble in water. Thus, low recoveries of “soluble” silver will result unless an alternative filter medium, such as polytetrafluoroethylene (PTFE), is used. Another problem is illustrated by soluble forms of Cr<sup>VI</sup>, which can react with the filter medium to form insoluble compounds and/or undergo reduction to Cr<sup>III</sup> and, therefore, be lost to Cr<sup>VI</sup> analysis. Hence, chemical compatibility issues must be investigated before samples meant for “soluble” extraction procedures are taken.

Membrane filters are appropriate for sampling aerosols for subsequent determination of soluble metal compounds. Such filters are manufactured from a variety of polymeric materials by a number of different processes. Choice of polymer material comprising the filter (e.g., MCE, PTFE, PVC) will depend on chemical reactivity issues discussed in the preceding paragraph. The metal content of the filters must be as low as possible, since it can make a significant contribution to the blank value.

## 5. ANALYTICAL CONSIDERATIONS

A number of analytical methods for soluble metal compounds in occupational hygiene samples have been published [10-13].

European Standard. Guidance on sample preparation methods for soluble metals and metalloids in workplace air has been promulgated recently in a European Standard [14]. In these published methods and guidelines [10-13,] two methodologies are generally favored for the extraction of “soluble” metal species: (1) extraction in pure water, or (2) extraction in diluted (~0.1 M) hydrochloric acid (HCl). In the European Standard [12,13], both strategies are given as options for the dissolution of “soluble” metals in workplace air samples. Extraction of metals and metalloids in water is meant to reflect the chemical definition of “soluble” (as mentioned above), while extraction in diluted HCl is designed to mimic the dissolution of “soluble” metal compounds in stomach acid, which is highly acidic (pH ≈ 1). A temperature of 37°C is recommended since this is normal body temperature.

Extraction Solvent. In a recent paper, [15] Hahn argued for the establishment of 0.1 M HCl in an operational definition for soluble metals in occupational hygiene samples and, also, specified mechanical agitation at 37°C for two hours prior to sample analysis. An exception is made for thallium, which can form insoluble TlCl, in which case HCl is replaced by diluted nitric acid (HNO<sub>3</sub>). (A similar problem would arise if HCl were used as the extraction acid for soluble silver compounds.) The German extraction method for several soluble metal species [13] is consistent with the strategy outlined by Hahn, [15] which attempts to address bioavailability by choosing HCl as the extraction acid. However, in standard methods promulgated by the United States, [10] the United Kingdom, [11] and France, [12] deionized water is the solvent chosen in the operational definition of “soluble” for numerous metallic elements in workplace air samples. An exception to extraction in water is made for nickel, [10] where an ammonium citrate solution is specified as the leachate for soluble compounds of this element. Ammonium citrate provides buffering and chelating properties that are desirable for leaching soluble nickel compounds [11].

Operation Definitions. Operational definitions of “soluble” metal species have been promulgated for consumer products such as toys, paper products, paints and art materials [16-18]. Standard procedures for the extraction of metal compounds from consumer products are based on sample treatments in 0.07 - 0.14 M HCl (depending on the sample) for an hour

at a temperature of 37°C [15] or at room temperature [17]. An American Society for Testing Material (ASTM) procedure [16] is meant to provide an estimate of the bioavailability of several metals in art materials, using ~0.1 M HCl and extraction at body temperature.

Quantity of Solvent. Another uncontrolled variable is the quantity of solvent used in laboratory analytical procedures for soluble metals at different laboratories. Different laboratories may (and do) use different amounts of deionized water for extraction. For example, one laboratory might use 10 mL of deionized water to extract the metal from a sample, while another lab may use anywhere from 25 to 100 mL to extract the compound. Depending upon the amount of material present in the sample, the procedure using 25 to 100 mL can dissolve a larger mass of solute than that using 10 mL. A conservative analytical method for metals used 15 mL of deionized water for extraction. This volume was chosen as a convenience and may not bear any relationship to what the body might absorb. Thus, two identical samples could produce two different results depending on the volume of solvent and other analytical parameters. A further factor affecting solubility is the particle size distribution of the sample: smaller particles are ordinarily more easily dissolved than larger ones. Thus for two samples having the same mass, the sample comprised of small particles may be more easily dissolved than a sample having large particles.

## 6. ISO PROCEDURE FOR SOLUBLE METALS AND METALLOIDS

Various procedures for the extraction of soluble metals and metalloids have been used for years, based on different operational definitions of solubility. The International Organization for Standardization, Technical Committee 146 on Air Quality, Subcommittee 2 on Workplace Atmospheres, Working Group 2 on Inorganic Particulate Matter (ISO/TC 146/SC 2/WG 2) has attempted to standardize extraction procedures for “soluble” metal compounds by offering an operational definition in terms of a sample preparation method for metallic elements in industrial hygiene measurements.

Bioavailability. In 1994, Fairfax and Blotzer argued that the solubility in body fluids should be considered in the development of a new definition for soluble TLVs [1]. But since different body fluids have different solubility characteristics (e.g., pH, salts, polypeptides), such an operational and uniform definition for “bioavailable” cannot realistically be decided. Indeed, the meaning of “bioavailability” has been debated nationally and internationally for years, and it was not deemed practicable nor defensible to attempt to operationally define solubility based on biochemical arguments. Hence, it was decided by consensus within the ISO working group (ISO/TC 146/SC 2/WG 2) to describe procedures for soluble metal compounds in terms of strictly chemical, and not biochemical, criteria [19].

Laboratory Consistency. With regard to analytical methods for the extraction of soluble metals and their compounds, Fairfax and Blotzer suggested that the extraction media, temperature, and extraction volume should be consistent among all laboratories [1]. For an operational definition of “soluble” to be offered, delineation of these analytical parameters is necessary in order to fully standardize the extraction procedure for soluble metal species. Moreover, the apparatus used, as well as chemical compatibility issues, must be amply described. Matters that are outside of laboratory control, notably sampling, cannot always be adequately influenced; however, recommendations as to sampling media, sample handling, and transport requirements should be provided to the field industrial hygienist.

Development of ISO Procedure. The ISO working group responsible for the development of ISO 15202-2, ISO/TC 146/SC 2/WG 2, began its task in September 1995, not long after the publication of the Fairfax and Blotzer article [1]. Shown in Table 2 is a list of countries that participated in voting on the technical content of the draft international standard when it was circulated for balloting, from 1996 to 2000.

**TABLE 2. “PARTICIPATING MEMBER”<sup>1</sup> COUNTRIES OF ISO/TC 146/SC 2 (DURING THE PERIOD OF DEVELOPMENT OF ISO 15202-2 [1996-2000])**

Belgium	Korea	Turkey
Germany	Netherlands	United Kingdom
India	Poland	United States
Italy	Spain	
Japan	Sweden	

<sup>1</sup>“Participating,” or P-Member, countries are those nations able to vote on Draft International Standards, and therefore may provide comments on the technical content of the documents during voting. “Observing,” or O-Member, nations (not listed) may also offer comments and can participate in the development of ISO standards. However, in the formal ISO voting process, O-member nations can vote only on Final Draft International Standards, which allows only for editorial, and not technical, changes at this stage.

Because of the various operational definitions for “soluble” metal compounds, a significant challenge was presented to the ISO working group responsible for the development of an international standard method to describe a procedure for extracting soluble metals and metalloids for subsequent atomic spectrometric analysis. Two choices were available based on the standard methods mentioned above: (1) extraction in pure water, or (2) extraction in 0.1 M HCL. It was decided by consensus of ISO delegates present at the earlier working group meetings to follow the former course, where solubility of metal compounds in occupational hygiene samples is defined in chemical terms. This decision was upheld during the later international voting process, which involved those countries listed in Table 2. Nevertheless, text within the International Standard [3] states that individual countries may specify alternative procedures for the measurement of soluble metal species in workplace air samples. This, then, leaves open the option to use other extraction media, such as 0.1M HCl.

The ISO procedure for soluble metals and metalloids assumes that samples were collected using the new International Standard for the collection of workplace air samples for subsequent multi-element analysis, ISO 15202-1 [20]. However, the choice of filter material used for the collection of samples targeted for the “soluble” metals procedure is important. Annex A of ISO 15202-1 [20] and Annex B of ISO 15202-2 [3] provide useful guidance on this subject.

The “soluble” metals procedure described in ISO 15202-2 [2] lists all of the elements in

Table 1 except for Cr<sup>VI</sup> and Fe. Nevertheless, the sample preparation protocol described in this International Standard is certainly applicable to these other two metallic elements as well. The ISO “soluble” metals method [3] calls for treatment of collected workplace filter samples in 5 mL of deionized water (or ammonium citrate leach solution in the case of Ni) and mechanical agitation in a water bath at 37 ± 2 °C for 60 min. Undissolved material is thereafter separated from the sample solution using a suction filtration apparatus or a syringe filter, and ensuring use of filtration materials that are unreactive towards the soluble metal compounds of interest. After filtration, the sample solution is acidified with nitric acid in order to stabilize the dissolved metallic elements within the extracted sample. This test sample is then ready for analysis by ICP-AES (or ICP-mass spectrometry if very low detection limits are required). Of course other analytical techniques, e.g., atomic absorption spectrometry [19,20] or electrochemical analysis [22,23] can be used as analytically equivalent alternatives.

## 7. SUMMARY

The exposure standards for some metals vary up to a factor of 500 to take into account the increased solubility and bioavailability of some compounds. Even compounds generally considered by chemists as being “insoluble” may have sufficient solubility in body fluids to be of biological importance. Exposure standards for soluble metals such as ACGIH TLVs are not specific with regard to extraction fluid, fluid temperature, agitation and other factors affecting solubility. Since these factors significantly affect solubility, some standardization or adoption of an operational definition is necessary if there is to be reproducibility among laboratories conducting soluble metal analyses. In some countries (e.g., nations in the European Union), the national requirements provide this specificity. In other instances, including exposure monitoring standards in the United States, formal national guidelines are not available.

Therefore, adherence to international extraction guidelines or methods such as those described in ISO standards is necessary to produce measurements that are reproducible with other laboratories, and have utility to the laboratory client when exposure standards or national guidelines are vague. ISO 15202 has the advantage over other guidelines and standards in that it has had input from more than (don’t forget that “O” members also have input) 13 participating countries (Table 2). Thus the use of ISO 15202 is encouraged until either exposure standards or national guidelines provide better specificity.

Laboratories cannot recover soluble metal data if inappropriate sample media are used. Sample stability is a problem that must be addressed when sampling for silver (Ag), chromium (Cr) and other soluble metal compounds. Although the ISO procedure has not been validated for all soluble metal species, the standard recommends that method validation be carried out using representative soluble metal compounds for target elements. ISO 15202 provides guidance on sample media selection for soluble metals that can be a useful guide for industrial hygienists and other laboratory clients.

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## 9. APPENDIX — Solubilities of Selected Metals and Metal Compounds<sup>[1]</sup>

### **Aluminum and compounds**

Aluminum metal reacts with dilute hydrochloric acid, sulfuric acid, potassium hydroxide, and sodium hydroxide.

The salts of aluminum, including sodium aluminate, aluminum fluoride, aluminum chloride, and cryolite, are all soluble in water.

### **Arsenic and compounds**

Arsenic — Insoluble in hot and cold water; soluble in nitric acid.

Arsenic trioxide and pentoxide — Soluble in cold and hot water, alcohol, alkalis, and hydrochloric acid; arsenic pentoxide is soluble in acids.

Lead arsenate — Insoluble in cold water; soluble in hot water, nitric acid, and caustic alkalis.

Calcium arsenate(s) — Insoluble in water and acids.

Sodium arsenate(s) — Very soluble in water.

Arsenic acid — Soluble in water and alcohol.

Arsenic trisulfide — Practically insoluble in water.

### **Barium and compounds**

Barium metal — Insoluble in water; soluble in alcohol.

Most of the compounds of barium are soluble in (cold or hot) water, for example, barium chloride, barium oxide, barium acetate, and barium cyanide. Barium hydroxide is slightly soluble in water. Barium carbonate is insoluble to slightly soluble in water, and is soluble in acids.

### **Beryllium and compounds**

Beryllium — Slightly soluble in hot water; insoluble in cold water; soluble in dilute alkalis and acids.

Beryllium oxide — Insoluble in water; soluble in some acids and alkalis.

Beryllium hydroxide — Insoluble in water; soluble in acids and alkalis.

Beryllium fluoride — Soluble in cold and hot water, alcohol, and sulfuric acid.

Beryllium sulfate — Soluble in water and concentrated sulfuric acid.

### **Chromium and compounds**

Chromium reacts with dilute hydrochloric acid and sulfuric acid, but not with nitric acid.

Chromium metal — Insoluble in hot and cold water.

Hexavalent chromium compounds, including chromium trioxide, the anhydride of chromic acid, chromates, dichromates, and polychromates, tend to be of low solubility in water and can be subdivided into two subgroups:

1. Water-soluble hexavalent chromium compounds include chromic acid, its anhydride, and the monochromates and dichromates of sodium, potassium, ammonium, lithium, cesium, and rubidium.
2. Water-insoluble hexavalent chromium compounds include zinc chromate, lead chromate, barium chromate, and sintered chromium trioxide.

NOTE: Depending on the reference [5,8], both calcium chromate and strontium chromate are listed as soluble and insoluble in water.

### **Iron and compounds**

Iron, ferrous oxide, ferric oxide, and iron oxide — Insoluble in hot and cold water.  
Ferric chloride, ferric nitrate, ferric sulfate, ferrous sulfate and ferrous chloride — Soluble in hot and cold water.  
Ferric chloride — Soluble in ethanol, methanol, and ether.  
Ferric nitrate and ferrous chloride — Soluble in ethanol and acetone.  
Ferric sulfate — Sparingly soluble in ethanol; insoluble in acetone.  
Ferrous sulfate — Insoluble in ethanol.

### **Molybdenum and compounds**

Molybdenum — Insoluble in hot or cold water; soluble in nitric, sulfuric, and hydrochloric acids.  
Molybdic oxide — Sparingly soluble in water; soluble in acids and alkalis.  
Molybdenum disulfide — Insoluble in hot or cold water and dilute acids; soluble in hot sulfuric acid, aqua regia, and nitric acid.  
Ammonium molybdate — Soluble in hot or cold water, acids, and alkalis.  
Calcium molybdate — Insoluble in cold water; soluble in hot water.  
Lead molybdate — Insoluble in water and alcohol; soluble in acid and potassium hydroxide.  
Sodium molybdate — Soluble in hot and cold water.

### **Nickel and compounds**

Nickel — Insoluble in hot and cold water; soluble in nitric, sulfuric, and hydrochloric acids.  
Nickel oxide — Insoluble in hot and cold water; soluble in ammonium hydroxide and acids.  
Nickel acetate — Soluble in cold water; insoluble in alcohol;<sup>[4]</sup> soluble in alcohol.<sup>[7]</sup>  
Nickel carbonate — Soluble in cold water; insoluble in hot water.  
Nickel hydrates — Some forms soluble, others insoluble (in water).  
Nickel sulfate — Soluble in hot and cold water.

### **Platinum and compounds**

Platinum — Insoluble in hot or cold water and single mineral acids; soluble in aqua regia; attacked by halogens, alkali cyanides, and caustic alkalis.  
Platinum forms are series of complex chloroplatinate salts that are water soluble.

### **Rhodium and compounds**

Rhodium — Insoluble in hot or cold water; soluble in hot sulfuric acid plus hydrochloric acid; slightly soluble in acids and aqua regia.  
Water-soluble rhodium compounds include rhodium trichloride, sodium chlororhodite, and rhodium carbonyl acetylacetonate.

### **Silver and compounds**

Silver — Insoluble in water and inert to most acids; reacts readily in dilute nitric acid or hot concentrated sulfuric acid; soluble in fused alkali hydroxides in the presence of air.  
Silver oxide — Soluble in hot and cold water, acids, and alkalis.  
Silver acetate — Soluble in hot or cold water and nitric acid.  
Silver bromide — Insoluble in hot or cold water and nitric acid.  
Silver chloride — Soluble in hot water; slightly soluble in cold water and ammonium hydroxide.  
Silver cyanide — Soluble in cold water, nitric acid, and ammonium hydroxide.

Silver nitrate — Soluble in hot and cold water.

### **Thallium and compounds**

Thallium — Insoluble in hot and cold water; soluble in nitric, sulfuric, and hydrochloric acids.

Thallic oxide — Soluble in water, acids, and alcohols.

Thallic oxide — Insoluble in hot or cold water; soluble in acids.

Thallic acetate and thallic chloride — Soluble in cold water and alcohol.

Thallic bromide and chloride — Slightly soluble in water.

Thallic sulfate — Soluble in hot or cold water.

Thallic sulfide — Soluble in cold water.

### **Tungsten and compounds**

Tungsten — Insoluble in hot or cold water, hydrofluoric acid, and potassium hydroxide; soluble in mixtures of hydrofluoric and nitric acid; slightly soluble in sulfuric acid.

Tungsten trioxide — Insoluble in hot or cold water and acids; soluble in hot alkalies and hydrofluoric acid.

Tungstic acid — Insoluble in cold water and most acids; soluble in hot water, alkalies, hydrofluoric acid, and ammonia.

Sodium tungstate — Soluble in hot and cold water; slightly soluble in ammonia; insoluble in acids and alcohol.

Tungsten carbide — Insoluble in water; soluble in mixtures of hydrofluoric and nitric acid, and in aqua regia.

Tungsten diboride — Insoluble in hot or cold water; soluble in aqua regia.

Tungsten hexachloride — Soluble in hot water.

Tungsten oxytetrachloride — Soluble in hot or cold water.

Tungsten hexafluoride — Soluble in hot or cold water and alkalies.

Tungsten disulfide — Insoluble in cold water and in alcohol; soluble in mixtures of hydrofluoric and nitric acid.

Phosphotungstic acid — Soluble in cold water, alcohol, and ether.

Ammonium paratungstate — Soluble in water; insoluble in alcohol.

### **Uranium and compounds**

Uranium — Insoluble in hot or cold water, alcohol, and alkali.

Uranium dioxide — Insoluble in hot or cold water; soluble in nitric acid and concentrated sulfuric acid.

Triuranium octoxide — Insoluble in hot or cold water; soluble in nitric acid and sulfuric acid.

Uranium tetrafluoride — Insoluble in cold water, dilute acids, and alkalies; soluble in concentrated acids and alkalies.