ACRYLAMIDE

1. Introduction

Acrylamide [79-06-1] (NIOSH No: A533250) has been commercially available since the mid-1950s and has shown steady growth since that time, but is still considered a small volume commodity. Its formula, $H_2C{=}CHCONH_2$ (2-propeneamide), indicates a simple chemical, but it is by far the most important member of the series of acrylic and methacrylic amides. Water soluble polyacrylamides

(1) represent the most important applications. The largest use in this catagory is as a dewatering aid for sludges in the treatment of effluent from municipal wastewater treatment plants and industrial processes.

Other uses include flocculants in feed water treatment for industrial purposes, the mining industry and various other process industries, soil stabilization, papermaking aids, and thickeners. Smaller but none the less important uses include dye acceptors; polymers for promoting adhesion; additives for textiles, paints, and cement; increasing the softening point and solvent resistance of resins; components of photopolymerizable systems; and cross-linking agents in vinyl polymers.

2. Physical Properties

Acrylamide is a white crystalline solid that is quite stable at ambient conditions, and, even at temperatures as high as its melting point (for 1 day in the absence of light), no significant polymer formation is observed. Above its melting point, however, liquid acrylamide may polymerize rapidly with significant heat evolution. Precautions should be taken when handling even small quantities of molten material. In addition to the solid form, a 50% aqueous solution of acrylamide is a popular commercial product today. This solution is stabilized by small amounts of cupric ion (25–30 ppm based on monomer) and soluble oxygen. Several other stabilizers are also available for the aqueous monomer solution, such as ethylenediaminetetraacetic acid (EDTA) [60-00-4] (2), ferric ion (3), and nitrite (4,5). The only effect of oxygen is to increase the induction period for polymerization (6). Iron complexes of cyanogen or thiocyanogen have proven to be useful stabilizers for salt-containing acrylamide solutions (7). The physical properties of solid acrylamide monomer are summarized in Table 1. Solubilities of acrylamide in various solvents are given in Table 2, and typical physical properties of a 50% solution in water appear in Table 3.

3. Chemical Properties

Acrylamide, C_3H_5NO, is an interesting difunctional monomer containing a reactive electron-deficient double bond and an amide group, and it undergoes reactions typical of those two functionalities. It exhibits both weak acidic and basic properties. The electron-withdrawing carboxamide group activates the double bond, that consequently reacts readily with nucleophilic reagents, eg, by addition.

$$\mathrm{Nuc:H} + \mathrm{CH_2{=}CHCONH_2} \longrightarrow \mathrm{NucCH_2CH_2CONH_2}$$

Many of these reactions are reversible, and for the stronger nucleophiles they usually proceed the fastest. Typical examples are the addition of ammonia, amines, phosphines, and bisulfite. Alkaline conditions permit the addition of mercaptans, sulfides, ketones, nitroalkanes, and alcohols to acrylamide. Good examples of alcohol reactions are those involving polymeric alcohols such as poly(vinyl alcohol), cellulose, and starch. The alkaline conditions employed with

Table 1. **Physical Properties of Solid Acrylamide Monomer**[a]

Property	Value
molecular weight	71.08
melting point, °C	84.5 ±
vapor pressure, Pa[b]	
25°C	0.9
40°C	4.4
50°C	9.3
boiling point, °C	
0.27 kPa[b]	87
0.67 kPa[b]	103
1.4 kPa[b]	116.5
3.3 kPa[b]	136
heat of polymerization, kJ/mol[c]	−82.8
density, g/mL at 30°C	1.122
equilibrium moisture content, particle size 355 μm[d], at 22.8°C, 50% rh	1.7 g of water/kg of dry acrylamide
crystal system	monoclinic or triclinic
crystal habit	thin tabular to laminar
refractive indexes	
n_x	1.460 (calcd)
n_y	1.550 ± 0.003
n_z	1.581 ± 0.003
optic axial angles	2E 98°, 2V 58°
optic sign	(−)

[a] Ref. 5.
[b] To convert kPa to mm Hg, multiply by 7.5.
[c] To convert kJ/mol to kcal/mol, divide by 4.184.
[d] 45 mesh.

Table 2. **Solubilities of Acrylamide in Various Solvents at 30°C**

Solvent	g/100 mL
acetonitrile	39.6
acetone	63.1
benzene	0.346
ethylene glycol monobutyl ether	31
chloroform	2.66
1,2-dichloroethane	1.50
dimethylformamide	119
dimethyl sulfoxide	124
dioxane	30
ethanol	86.2
ethyl acetate	12.6
n-heptane	0.0068
methanol	155
pyridine	61.9
water	215.5
carbon tetrachloride	0.038

Table 3. **Physical Properties of 50% Aqueous Acrylamide Solution**[a]

Property	Value
pH	5.0–6.5
refractive index range, 25°C (48–52%)	1.4085–1.4148
viscosity, mPa (= cP) at 25°C	2.71
specific gravity, at 25°C	1.0412
density, 25/4°C	1.038
crystallization point, °C	8–13
partial phase diagram	
eutectic temperature, °C	−8.9
eutectic composition, wt%	31.2
boiling point at 101.3 kPa,[b] °C	99–104
vapor pressure	
at 23°C, kPa[b]	2.407
at 70°C, kPa[b]	27.93
specific heat (20–50°C), (20–50°C),J/(g · K)[c]	3.47
heat of dilution to 20 wt%, J/g soln[c]	−4.6
heat of polymerization, kJ/mol[c]	−85.4
heat of melting (solution), melting range −17.3 to + 19.7°C, J/g[c]	247.7
flammability	nonflammable

[a] Ref.5.
[b] To convert kPa to mm Hg, multiply by 7.5.
[c] To convert J to cal, divide by 4.184.

these reactions result in partial hydrolysis of the amide, yielding mixed carbamoylethyl and carboxyethyl products.

Some specific examples include the noncatalytic reaction of acrylamide with primary amines to produce a mono or bis product (5).

$$RNH_2 + CH_2{=}CHCONH_2 \longrightarrow RNHCH_2CH_2CONH_2 \longrightarrow RN(CH_2CH_2CONH_2)_2$$

Secondary amines give only a monosubstituted product. Both of these reactions are thermally reversible. The product with ammonia (3,3′,3″-nitrilotrispropionamide [2664-61-1], $C_9H_{18}N_4O_3$) (5) is frequently found in crystalline acrylamide as a minor impurity and affects the free-radical polymerization. An extensive study (8) has determined the structural requirements of the amines to form thermally reversible products. Unsymmetrical dialkyl hydrazines add through the unsubstituted nitrogen in basic medium and through the substituted nitrogen in acidic medium (9). Monoalkylhydroxylamine hydrochlorides react with preservation of the hydroxylamine structure (10). Primary nitramines combine in such a way as to keep the nitramine structure intact.

The reaction with sodium sulfite or bisulfite (5,11) to yield sodium-β-sulfopropionamide [19298-89-6] ($C_3H_7NO_4S{\cdot}Na$) is very useful since it can be used as a scavenger for acrylamide monomer. The reaction proceeds very rapidly even at room temperature, and the product has low toxicity. Reactions with phosphines and phosphine oxides have been studied (12), and the products are potentially useful because of their fire retardant properties. Reactions with sulfide and dithiocarbamates proceed readily but have no applications (5). However, the reaction with mercaptide ions has been used for analytical purposes (13).

Water reacts with the amide group (5) to form hydrolysis products, and other hydroxy compounds, such as alcohols and phenols, react readily to form ether compounds. Primary aliphatic alcohols are the most reactive and the reactions are complicated by partial hydrolysis of the amide groups by any water present.

Activated ketones react with acrylamide to yield adducts that frequently cyclize to lactams (14). The lactams can be hydrolyzed to yield substituted propionic acids. Chlorine and bromine react with acrylamide in aqueous solution to yield α,β-dihalopropionamide (5). Under acidic conditions, sizable quantities of acrylamide can be removed from water by chlorination (15). Hydrochloric and hydrobromic acids add to give β-halopropionamides. These adducts are also thermally reversible. A patent describes a procedure to prepare *N*-substituted acrylamide by direct transamidation of acrylamide (16). Dienes react with acrylamide to form Diels-Alder type adducts (17,18). Improved yields in the aza-annelation of cyclic ketones by the use of enamines and imines have been reported (19–21). Palladium reduced with borohydride (22), nickel boride (23), or rhodium carbonyl (24) reduces the double bond of acrylamide to yield propionamide, and acrylamide can be oxidized to a glycol with sodium hypochlorite using osmium tetroxide as a catalyst (25). In contrast, if osmium is not present, the attack occurs at the nitrogen to yield *N*-vinyl-*N*′-acryloylurea [19396-55-5] ($C_6H_8N_2O_2$) (26). When treated with a strong base in an aprotic solvent, acrylamide forms a head-to-tail dimer, 3-acrylamidopropionamide [21963-06-4]($C_6H_{10}N_2O_2$) (27). Electrolytic reductive dimerization of acrylamide proceeds through tail-to-tail addition to yield adipamide [628-94-4], ($C_6H_{12}N_2O_2$) (28).

The most important reactions of acrylamide are those that produce vinyl addition polymers (see ACRYLAMIDE POLYMERS). The initiation and termination mechanisms depend on the catalyst system, but the reaction can be started by any free-radical source. In practice, redox couples such as sodium persulfate and sodium bisulfite are commonly used, and the highest molecular weight polymers are obtained in aqueous solution, with molecular weights of several million prepared routinely. Acrylamide is remarkable for the very large value of $k_p/k_t^{1/2}$, $1.8 \times 10^4/(1.45 \times 10^7)^{1/2}$, which is a measure of chain length in the polymerization. However, it may be necessary to remove the inhibitor (cupric ions) from aqueous acrylamide solutions to obtain the desired polymerization results. Copolymers with acrylamide are also prepared with ease, although the molecular weights are consistently lower than that of polyacrylamide prepared under similar conditions. Acrylamide copolymerizes readily by a free-radical mechanism with other acrylates, methacrylates, and styrene. Acrylamide may be polymerized by a hydrogen-transfer mechanism catalyzed by strong base in basic or aprotic solvents. The product is poly(β-alanine) or nylon-3 (29), which has properties similar to natural silk. This polymer, on hydrolysis, yields β-aminopropionic acid. A hydrogen-transfer copolymer with acrolein has also been reported (30). A biocatalytic method of removing residual monomer from polymers that could become very important to acrylamide polymer users has been described (31).

The amide group is readily hydrolyzed to acrylic acid, and this reaction is kinetically faster in base than in acid solutions (5,32,33). However, hydrolysis of *N*-alkyl derivatives proceeds at slower rates. The presence of an electron-withdrawing group on nitrogen not only facilitates hydrolysis but also affects the polymerization behavior of these derivatives (34,35). With concentrated sulfuric

acid, acrylamide forms acrylamide sulfate salt, the intermediate of the former sulfuric acid process for producing acrylamide commercially. Further reaction of the salt with alcohols produces acrylate esters (5). In strongly alkaline anhydrous solutions, a potassium salt can be formed by reaction with potassium *tert*-butoxide in *tert*-butyl alcohol at room temperature (36).

Several other interesting reactions include acrylamide transition metal complexes (37–40), complexes with nucleosides (41) in dimethyl sulfoxide solution, and also complexes with several inorganic salts (42–44). Dehydration of acrylamide by treatment with fused manganese dioxide (45) at 500°C or with phosphorus pentoxide (46) yields acrylonitrile. Aldehydes such as formaldehyde, glyoxal, and chloral hydrate react with acrylamide under neutral and alkaline conditions, producing the corresponding *N*-methylolacrylamide [924-42-5] (47,48). Under acidic conditions, *N*,*N*-methylenebisacrylamide [110-26-9] [$(H_2C{=}CHCONH)_2CH_2$] is produced from formaldehyde and acrylamide (49). Under acidic conditions, methoylol ethers are formed from hydroxyl compounds and *N*-methylolacrylamide (50). Condensation products derived from *N*-methylolacrylamide and polyphenols have also been reported (51). By using *p*-toluenesulfonic acid as the catalyst in dioxane or ethyl acetate solvent, *N*,*N*′-oxydimethylenebisacrylamide [16958-71-7] ($C_8H_{12}O_3N_2$) has been obtained (52). These difunctional products have similar copolymerization parameters to acrylamide and are useful as cross-linking agents. Alcohols can be used to cap the methylol compound to provide the less reactive methylol ethers. Methanol is commonly employed, but, where increased compatibility with oleophilic systems is desired, one of the butanols is the preferred alcohol; oxalic acid is an example of a suitable catalyst (50). This reaction also occurs with cellulosic hydroxyls. Provided the system is not basic, the methylol derivative may also be condensed with carbamate esters (53), secondary amines (54), or phosphines (12) without involving the double bond. Acrylamido-*N*-glycolic acid and diacrylamidoacetic acid can be obtained from acrylamide and glyoxylic acid (55–58). *N*-Acylacrylamides are of minor interest industrially. One member of the series, diacrylamide [20602-80-6] ($C_6H_7NO_2$), is a suspected side-reaction product in the sulfuric acid process of manufacture. It may be prepared by the reaction of acrylamide with acrylic anhydride or acryloyl chloride. A specific preparation for *N*-acetylacrylamide [1432-45-7] ($C_5H_7NO_2$) is the addition of ketene to acrylamide (59).

4. Manufacture

The current routes to acrylamide are based on the hydration of inexpensive and readily available acrylonitrile [107-13-1] (C_3H_3N, 2-propenenitrile, vinyl cyanide, VCN, or cyanoethene) (see ACRYLONITRILE). For many years, the principal process for making acrylamide was a reaction of acrylonitrile with $H_2SO_4{\cdot}H_2O$ followed by separation of the product from its sulfate salt using a base neutralization or an ion exclusion column (60).

$$CH_2{=}CHCN + H_2SO_4{\cdot}H_2O \longrightarrow CH_2{=}CHCONH_2{\cdot}H_2SO_4$$

This process yields satisfactory monomer, either as crystals or in solution, but it also produces unwanted sulfates and waste streams. The reaction was usually

run in glass-lined equipment at 90–100°C with a residence time of 1 h. Long residence time and high reaction temperatures increase the selectivity to impurities, especially polymers and acrylic acid, which controls the properties of subsequent polymer products.

The ratio of reactants had to be controlled very closely to suppress these impurities. Recovery of the acrylamide product from the acid process was the most expensive and difficult part of the process. Large scale production depended on two different methods. If solid crystalline monomer was desired, the acrylamide sulfate was neutralized with ammonia to yield ammonium sulfate. The acrylamide crystallized on cooling, leaving ammonium sulfate, which had to be disposed of in some way. The second method of purification involved ion exclusion (60), which utilized a sulfonic acid ion-exchange resin and produced a dilute solution of acrylamide in water. A dilute sulfuric acid waste stream was again produced, and, in either case, the waste stream represented a problem as well as an increased production cost. As far as can be determined, no commercial acrylamide is produced today via this process.

Even in 1960, a catalytic route was considered the answer to the pollution problem and the by-product sulfate, but nearly 10 years elapsed before a process was developed that could be used commercially. Some of the earlier attempts included hydrolysis of acrylonitrile on a sulfonic acid ion-exchange resin (61). Manganese dioxide showed some catalytic activity (62), and copper ions present in two different valence states were described as catalytically active (63), but copper metal by itself was not active. A variety of catalysts, such as Urushibara or Ullmann copper and nickel, were used for the hydrolysis of aromatic nitriles, but aliphatic nitriles did not react using these catalysts (64). Beginning in 1971, a series of patents were issued to The Dow Chemical Company (65) describing the use of copper metal catalysis. Full-scale production was achieved the same year. A solution of acrylonitrile in water was passed over a fixed bed of copper catalyst at 85°C, which produced a solution of acrylamide in water with very high conversions and selectivities to acrylamide. The heat of hydration is approximately −70 kJ/mol (−17 kcal/mol). This process usually produces no waste streams, but if the acrylonitrile feed contains other nitrile impurities, they will be converted to the corresponding amides. Another reaction that is prone to take place is the hydrolysis of acrylamide to acrylic acid and ammonia. However, this impurity can usually be kept at very low concentrations.

Mitsui Toatsu Chemical, Inc. disclosed a similar process using Raney copper (66) shortly after the discovery at Dow, and BASF came out with a variation of the copper catalyst in 1974 (67). Since 1971, several hundred patents have shown modifications and improvements to this technology, both homogeneous and heterogeneous, and reviews of these processes have been published (68). Nalco Chemical Company has patented a process based essentially on Raney copper catalyst (69) in both slurry and fixed-bed reactors and produces acrylamide monomer mainly for internal uses. Other producers in Europe, besides Dow and American Cyanamid, include Allied Colloids and Stockhausen, who are believed to use processes similar to the Raney copper technology of Mitsui Toatsu, and all have captive uses. Acrylamide is also produced in large quantities in Japan.

In 1985, Nitto Chemical Industry started using microorganisms for making acrylamide from acrylonitrile using an enzymatic hydration process (71,78). The

reaction is catalyzed by nitrile hydralase, a nitrilasically active enzyme produced by organisms such as *Corynebacterium N-774* strain, *Bacillus*, *Bacteridium*, *Micrococcus*, *Nocardia*, and *Pseudomonas*. This is one of the initial uses of biocatalysis in the manufacture of commodity chemicals in the petrochemical industry. There are certainly other bioprocesses in use for fine chemicals in the amino acid area, as well as fermentation processes. Improved bacterial strains and cells immobilized in acrylamide gels as well as methods of concentrating the dilute product solutions are subjects of more recent patents (72–74). The most recent release indicates a switch to *Rhodococcus rhodochrous* bacteria, which will increase their capacity from 6000 to 20,000t/year (75). The reaction is run at 0–15°C and a pH 7–9 and gives almost complete conversions with very small amounts of by-products such as acrylic acid.

Acrylamide and its derivatives have been prepared by many other routes (4). The reactions of acryloyl chloride and acrylic anhydride with ammonia are classical methods. Primary and secondary amines may be used in place of ammonia to obtain *N*-substituted derivatives. Acryloyl isocyanate has been hydrolyzed to acrylamide but yields are poor. Exhaustive amination of methyl acrylate with ammonia yields 3,3′,3″-nitrilotrispropionamide [2664-61-1] ($C_9H_{18}N_4O_3$). This compound can be thermally decomposed to acrylamide by heating to 208–230°C at 2 kPa (15 mm Hg). Similarly, Michael-type addition products of alkylamines or aliphatic alcohols and methyl acrylate react with ammonia to give the corresponding β-substituted propionamides. These compounds may also be thermally decomposed to yield acrylamide. The Michael-type addition products of methyl acrylate and aliphatic amines may react further to give *N*-alkyl or *N*,*N*-dialkyl propionamide derivatives that can be thermally decomposed to monoalkyl- or dialkyl-substituted acrylamides, respectively. *N*-Substituted acrylamides may also be prepared from acetylene, carbon monoxide, and an amine using an iron or nickel carbonyl catalyst. However, the best route to mono-*N*-alkyl-substituted acrylamides is the Ritter reaction. This reaction is used to prepare diacetoneacrylamide [2873-97-4] ($C_9H_{15}NO_2$), 2-acrylamido-2-methylpropanesulfonic acid [15214-89-8] ($C_7H_{13}NO_4S$), *N*-isopropylacrylamide [2210-25-5] ($C_6H_{11}NO$), *N*-tert-butylacrylamide [107-58-4] ($C_7H_{13}NO$), and other *N*-alkyl acrylamides in which the carbon attached to the nitrogen is usually tertiary (76,77).

A process for manufacturing acrylamide microemulsified homopolymer has been disclosed (78).

5. Economic Aspects

Seventy percent of the world capacity of acrylamide is in the United States, Western Europe, and Japan. Western Europe and the United States consume ~48% of the supply or water management and paper production. For Japan and the rest of the world, the main uses are in paper production and enhanced oil recovery (79)

U. S. producers of acrylamide and their capacities are given in Table 4.

Prices for the period 1996–2001 were in the range of $0.80/kg ($1.76/lb)–$0.84/kg ($1.86/lb). Prices were for a 50% solution, 100% basis, bulk, and fob works. Current prices are the same and on the same basis (1).

Table 4. **U. S. Producers of Acrylamide and Their Capacities**[a]

Producer	Capacity $\times 10^3$t($\times 10^6$ lb)
Ciba Specialty Chemicals, Suffolk, Va.	15 (33)
Cytec Industries, Avondale, La.	41 (90)
Ondeo Nalco, Garyville, La.	16 (35)
SNF Floerger, Riceboro, Ga.	65 (143)
Total	*137 (301)*

[a] Ref. 1.

6. Specifications

The 50% aqueous acrylamide is the preferred form because it eliminates the handling of solids and because its cost is lower. This result is of the new manufacturing method put into effect in 1971. The aqueous form is applicable to nearly all the end uses of acrylamide when volume is taken into account. Aqueous acrylamide is shipped in tank trucks, rail cars, or drums, but small samples can also be obtained. The solution should be kept in stainless steel or in tanks coated with plastic resin (phenolic, epoxy, or polypropylene). All containers, including tank trucks and rail cars, must be rinsed prior to disposal or return. When shipping costs are an important consideration, solid acrylamide may be the desired form. Acrylamide should be stored in a well-ventilated area away from sunlight. The temperature should be $<30^{\circ}$C, and under these conditions no change of quality should be noticed for at least 3 months. Typical specifications for the 50% aqueous solution are shown in Table 5 and for the solid monomer in Table 6.

Table 5. **Typical Specifications for 50% Aqueous Solutions**[a]

Property	Limit
assay, wt %	48–52
pH	5.0–6.5
polymer, ppm, max (BOM)[b]	100
Cu^{2+} inhibitor, ppm, max (BOM)[b]	25
color	water clear

[a] Refs.11, 81.
[b] Based on monomer = BOM.

Table 6. **Typical Specifications for Crystalline Acrylamide Monomer**

appearance	white, free flowing crystal
assay, %, min	98
water, %, max	0.8
iron, as Fe^0, ppm, max	15
color, 20% soln, max, APHA	50
water insoluble, %, max	0.2
butanol insoluble, %, max	1.5

Table 7. **Acrylamide Assay Techniques**[a]

Method	Approximate sensitivity, ppm[b]	Application	Interference	References
refractive index	50,000	quality control	anything affecting refractive index	11,81
bromate–bromide	1,000	assay product	unsaturated compounds	5
flame ionization	40	monomer in polymer		86
dc polarization	10	assay product	alkali cations, acrylic esters	84
differential pulse polarography	>1	environment concerns	alkali cations, acrylic esters, vinyl cyanide	82
spectrophotometry	0.1	urinalysis	aldehydes, ketones, pyrroles, indoles, hydrazine, aromatic amines	84,85
hplc	0.1	wipe and air		87
electron capture, gc	0.1 ppb	river water		83

[a] Ref. 85.
[b] Unless otherwise noted.

7. Analytical and Test Methods

The analysis of acrylamide monomer in water solutions containing at least 0.5% monomer is carried out by bromination (5). If the concentration is fairly high, in the 2–55% monomer range, then a refractive index method is easier (11,80,81). Polarography (82) and gas chromatography (83) can also be used to determine trace amounts of acrylamide monomer in other organic materials. For detecting small concentrations of polymer in aqueous acrylamides solutions, *n*-butanol addition will produce turbidity, which can then be compared to standards (5,81). Cupric ion inhibitor and other impurities in acrylamide samples can be determined by standard techniques (11,81,84). Other methods can also be employed to analyze the polyacrylamide content of monomer solutions, including turbidimeteric (Hach) and colorimetric (Klett) methods (11,81). A summary of various analytical techniques for assaying acrylamide monomer are listed in Table 7.

8. Health and Safety Factors

Contact with acrylamide can be hazardous and should be avoided. The most serious toxicological effect of exposure to acrylamide monomer is as a neurotoxin.

In contrast, polymers of acrylamide exhibit very low toxicity. Since the solid form sublimes, the solid or powder form of acrylamide is more likely to be a problem than the aqueous form because of possible exposure to dusts and vapors. An important characteristic of the toxicity of acrylamide monomer is that the signs and symptoms of exposure to toxic levels may be slow in developing and can occur after ingestion of small amounts over a period of several days or weeks. It is therefore important that people who have been exposed to acrylamide be monitored by a qualified physician. Signs and symptoms include increased sweating of hands and feet, numbness or tingling of the extremities, or even paralysis of the arms and legs. Acrylamide is readily absorbed through unbroken skin, and the signs are the same as with ingestion. Acute dermal LD_{50} is 2250 mg/kg for rabbits (77). Eye contact can produce conjunctival irritation and slight corneal injury and can lead to systemic exposure if contact is prolonged and/or repeated. Inhalation of vapors, dusts, and/or mists can result in serious injury to the nervous system, but again, symptoms may be slow in developing. Since the symptoms for minor repeated exposures over a long period of time are similar to those for gross human exposure, the development of such symptoms can be a signal that severe damage has already occurred. There are no reliable "early warning" signals of damaging exposure to toxic levels of acrylamide monomer, so it is imperative that all handling procedures be designed to prevent human contact. In a long-term study, rats that received relatively low concentrations of acrylamide monomer in the drinking water showed an increase in several types of malignant tumors (88). Suitable respirators and clothing that consists of a head covering, long-sleeved coverall, impervious gloves, and rubber footwear are recommended to avoid contact (81).

A large number of research studies have been published, many of which were released by government agencies (89–96). A threshold limit value (TLV) of 0.03 mg/m^3 (skin) has been set by the American Conference of Governmental Industrial Hygienists (ACGIH). ACGIH also categorizes acrylamide as A2 (suspect human carcinogen). Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) is 0.3 mg/m^3 (98). Several studies demonstrate that acrylamide is biodegradable (97), and the hydrolysis of acrylamide proceeds readily both in rivers and in soils (99,100). Bioconcentration of acrylamide probably will not occur because of the ease of biodegradation and the high water solubility of this material. Acrylamide shows low acute toxicity to fish (61,101). Other derivatives, such as *N*-methylolacrylamide, are neurotoxins in their own right, but the LD_{50} is much higher than for acrylamide. Toxicity data for acrylamide and several derivatives are listed in Table 8.

Handling of dry acrylamide is hazardous primarily from its dust and vapor, and this is a significant problem, especially in the course of emptying bags and drums. This operation should be carried out in an exhaust hood with the operator wearing respiratory and dermal protection. Waste air from the above mentioned ventilation should be treated by a wet scrubber before purging to the open air, and the waste water should be fed to an activated sludge plant or chemical treatment facility. Solid acrylamide may polymerize violently when melted or brought into contact with oxidizing agents. Storage areas for solid acrylamide monomer should be clean and dry and the temperature maintained at 10–25°C, with a maximum of 30°C.

Table 8. **Toxicity of Acrylamide and Derivatives**

Compound	CAS Registry Number	Molecular formula	Animal	Oral LD_{50}, g/kg	References
acrylamide	[79-06-1]	C_3H_5NO	mouse	0.17	77
N-methylolacrylamide	[924-42-5]	$C_4H_7NO_2$	mouse	0.42	102
N,N′-methylenebisacrylamide	[110-26-9]	$C_7H_{10}N_2O_2$	rat	0.39	103
N-isobutoxymethylacrylamide	[16669-59-3]	$C_8H_{15}NO_2$	rat	1.0	104
N,N-dimethylacrylamide	[2680-03-7]	C_5H_9NO	rat	0.316	105
2-acrylamido-2-methylpropane-sulfonic acid	[15214-89-8]	$C_7H_{13}NO_4S$	rat	1.41	106

The 50% aqueous product is the most desirable where water can be tolerated in the process. Employees should not be permitted to work with acrylamide until thoroughly instructed and until they can practice the required precautions and safety procedures. Anyone handling acrylamide should practice strict personal cleanliness and strict housekeeping at all times. This should include wearing a complete set of clean work clothes each day and the removal of contaminated clothing immediately. If contact is made, the affected skin area should be washed thoroughly with soap and water and contaminated clothing should be replaced. When contact can occur, such as in maintenance and repair operations or connection and disconnection during transport, protective equipment should be used. This should include impervious gloves and footwear to protect the skin, and suitable eye protection such as chemical worker's goggles. If exposure to the face is possible, a face shield should be used in addition to the goggles. Food, candy, tobacco, and beverages should be banned from areas where acrylamide is being handled, and workers should wash hands and face thoroughly with soap and water before eating or drinking. The need for good personal hygiene and housekeeping to prevent exposure cannot be overemphasized.

Aqueous solutions of 50% acrylamide should be kept between 15.5 and 38°C with a maximum of 49°C. Below 14.5°C acrylamide crystallizes from solution and separates from the inhibitor. Above 50°C the rate of polymer buildup becomes significant. Suitable materials of construction for containers include stainless steel (304 and 316) and steel lined with plastic resin (polypropylene, phenolic, or epoxy). Avoid contact with copper, aluminum, their alloys, or ordinary iron and steel.

Disposal of small amounts of acrylamide may be done by biodegradation in a conventional secondary sewage treatment plant, but any significant amounts should be avoided. Such waste material should not be allowed to get into a municipal waste treatment or landfill operation unless all appropriate precautions have been taken. When the disposal of large quantities is necessary, the supplier should be contacted. Containers that have been used for acrylamide should be thoroughly rinsed and then disposed of in an appropriate manner. In any disposal of waste materials, all of the applicable federal, state, and local statutes, rules, and regulations should be followed. Persons contemplating large-scale use of acrylamide monomer should consult the manufacturers at an early stage in the planning to ensure that their facilities and operations are adequate. Many companies refuse to supply to operations that, in their opinion, are unsafe.

9. Uses

The largest use of acrylamide in the United States is for the production of polyacrylamides and consumes 94% of the total. In this category, the largest use of polyacrylamides is in water treatment, which accounts for 56%. This includes use as a dewatering aid for sludge in the treatment of effluent from municipal wastewater treatment plants (eg, sewage) and industrial processes (pulp and paper plant wastewater). Polyacrylamides are also used as flocculents for feed water treatment for industrial purposes. Other uses include in pulp and paper

production (24%), mineral processing (10%), *N*-methylacrylamide and other monomers (6%), and miscellaneous (4%) (1).

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