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Bibliography of Work on the Photocatalytic Removal of Hazardous Compounds from Water and Air

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Summary

The DOE Solar Industrial Program is carrying out research and development on solar processes for destroying or removing hazardous substances from water and air. The processes are based on the photocatalytic action of titanium dioxide.

This report provides a bibliography of work done on the photocatalytic oxidation of organic or inorganic compounds in air or water and on the photocatalytic reduction of metal containing ions in water. The bibliography includes information obtained through the middle of 1993 and some selected references from the balance of that year. The general focus of the work is removing hazardous contaminants from air or water to meet environmental regulations. The information is organized in a way that provides citations for work done in a few broad categories that are generic to the process. The work on specific substances is presented in three tables. The first covers organic compounds that are included in various lists of hazardous substances identified by the United States Environmental Protection Agency (EPA). The second lists compounds not included in those categories, but which have been treated in a photocatalytic process. The third covers inorganic compounds that are on EPA lists of hazardous materials or that have been treated by a photocatalytic process.

Table of Contents

1 .O Introduction

This report provides scientists and engineers interested in applications of solar or photocatalytic detoxification in environmental chemistry with a comprehensive bibliography of work available in the open literature. The literature cited, including United States and foreign patents, dates from 1970 to the middle of 1993. It has been compiled by manually scanning the literature and searching commercial databases. The information is maintained at the National Renewable Energy Laboratory in Golden, Colorado, in a Procite database. Some citations may have been missed and topics covered in certain papers may not have been identified and covered in every appropriate category.

The photocatalytic oxidation of organic compounds in water is the subject of a large body of research that has been performed in laboratories all over the world. A lesser amount of effort has been devoted to removing inorganic substances from water or to oxidizing compounds in the gas phase. The general reaction is summarized as follows:

$$\text{Red(aqueous)} + O_2\text{(aqueous)} \xrightarrow[h\upsilon]{\text{Semiconductor}} \text{Oxid(aqueous)} + H_2O$$

The net process involves oxidizing the organic compound to an intermediate stage of oxygen content or to carbon dioxide, water, and a mineral acid (if a heteroatom such as nitrogen or chlorine is present). Other oxidizing agents may be substituted for oxygen. Modifying or removing certain metal ions from water can be accomplished when the agents replace oxygen as the electron acceptor in the process. A similar equation can be written to represent the oxidation of substances in the gas phase when the agents come in contact with an illuminated semiconductor photocatalyst.

The following sections cover reviews written on various aspects of the technology, work in developing and testing photocatalysts and oxidants, engineering issues, and other topics. These generic sections are followed by a list of work performed on specific substances. Papers referring to work on gas phase mixtures are indicated by the prefix "g" in the citation number.

2.0 Generic Information

This section refers to work that cuts across the field of photocatalytic processes for environmental applications.

2.1 Review Articles

A number of reviews have been written that cover various aspects of photocatalytic chemistry and technology. These can be found in the following references: 23, 26, 64, 65, 98, 103, 116, 150, 155, 186, 195, 201, 204, 221, 263, 309, 317, 331, 360, 411, 439, 449, 457, 458, 459, 496, 498, 512, 524, 533, 544, 559, 590, 599, 615, and 644, 648, 649, 653, 654, 661, and 663. The Proceedings of the 1st International TiO_2 Conference contain 78 papers, most of which are not included individually in the bibliography reference 656.

2.2 Photocatalysts

The nature of the photocatalyst determines the rate and efficiency of the process. The anatase form of titanium dioxide has the desirable properties of being chemically stable, readily available, and active as a catalyst for oxidation processes. On the negative side, its 3.2 eV band gap results in only a small overlap of its action spectrum with the solar spectrum. Also, the efficiency for converting photons absorbed to hazardous molecules destroyed is generally low (generally less than 5% in aqueous phase reactions). To identify the reasons for the low quantum yields and to improve the overlap of the absorption spectrum of the photocatalyst with the solar spectrum, a great deal of work has been done on modifying TiO_2 and testing other semiconductors. This work is broken down into a few broad categories and covered in the references cited.

2.2. I Modified Titanium Dioxide

Titanium dioxide and modified forms including different commercially available forms, heat treated materials, and materials prepared by a range of techniques: 17, 18, 39, 56, 72, 84, 113, 116, 132, 146, 156, 170, 172, 189, 228, 232, 253, 262, 266, 267, 290, 316, 334, 389, 395, 416, 419, 431, 432, 488, 495, 501, 507, 515, 517, 518, 535, 551, 555, 558, 562, 563, 565, 598, 600, 601, 604, 612, 615, 620, 623, 631, 632, and 642.

2.2.2 Hydrophobic Surface Treatment

Titanium dioxide has been modified to make the surface hydrophobic to alter the interaction with organic compounds in water. This work is covered in the following: 19, 210, 215, 268, and 436.

2.2.3 Dye Sensitized Titanium Dioxide

Dye sensitizers have been used in conjunction with titanium dioxide to improve the response to visible light: 53, 140,142, 144, 183, 280, 28 1, 282, 283, 483, and 619.

2.2.4 Metal Ion Doping of Titanium Dioxide

Other metal ions have been introduced into the titanium dioxide lattice to modify the properties. They are covered in the following: Si - 27, 206, 367, 368, 504, and 566; Li-288; Al-27, 565; Mg-242; V-26 and 265; Cr-315, and 510; Mn-241, and 324; Fe-57, 104, 403, 404, 405, 406, 541, and 579; Y-241; Nb-491; Mo-2, 26, 315; W-124, 184, 568, and 573; and Ru-2, 47, and 191.

2.2.5 Metallized Titanium Dioxide

Noble metals have been deposited on the titanium dioxide surface to enhance electron transfer: Ni-454; Cu-193; Rh-205; Pd-205, 302, 413, 435, and 602; Ag-3, 197, 205, 233, 243, 279, 415, and 419; Pt-2, 24, 25, 29, 50, 51, 90, 92, 97, 133,134, 139, 170, 191, 192, 193, 198, 205, 206, 208, 243, 257, 264, 295, 314, 338, 344, 393, 394, 413, 454, 496, 497, 506, 522, 532, 540, 546, 552, 555, 574, 595, 617, 618, 621, 625, g656, and g657; Ag-8, 169, 618, and 630; and Hg-243.

2.2.6 Other Semiconductors

A wide range of other semiconductors have been tested for photocatalytic activity. In general they have been found to be less active than titanium dioxide. Relevant work is cited in the following: Sr-or $BaTiO_3$-191, 309, 382, and 506; V_2O_5- 201; Fe_2O_3-3, 41, 548, 642, FeO(OH)-179; ZnO-3, 29, 156, 172, 242, 261, 326, 372, 374,375, 376, 437, 450, 477, 506, 548, and 569; Zn- or CdS- 41, 47, 375, 420, 613, and 625; ZnO/Pt-29; ZrO2-17 and 156; MoO_3-17; MoS_2-280; SnO_2- 156; WO_3-338, 506, and 548; SiO_2-375; TiO/N-224; and Natural Minerals-255, 256, 425,437, 441, and 646.

2.2.7 Immobilized Photocatalysts

Most experimental work on aqueous systems has been performed using the photocatalyst in the form of fine particles suspended in the liquid phase. In a waste treatment application it would be simpler if the catalyst were immobilized in the photoreactor so the material would not have to be separated from the treated fluid in a subsequent process step. Titanium dioxide has been affixed to a variety of surfaces in attempts to solve this problem. The following refer to the surfaces indicated: Glass-2, 23, 28, 97, 165, 198, 228, 355, 396, 474, 485, 486,487, and 527; Metal-167, 323, 384, 499, and 629; Ceramic-20, 101, 228, 362, 367, 372, 489, 490, 547, 550, 562, 582, 628, and 633; Polymer-52, 66, 89, 196,209, 228,236, 285, 382, 383, and 633; and Thin Film-112, 170, 248,481, and 563.

2.3 Hydrogen Peroxide and Related Oxidants

Oxygen has been the oxidant of choice in most studies, but hydrogen peroxide has been found to improve the rates of reaction with a variety of organic substrates. This work is covered in the following: 10, 32, 72, 86, 100, 160, 162, 163, 164, 182, 186, 187, 194, 228, 229, 260, 278, 291, 293, 317, 320, 331, 357, 362, 376, 377, 390, 391, 392, 397, 423, 430, 500, 517, 528, 552,556, 557,594, 608, 609, and 621.

2.4 Engineering Issues

In recent years the success of laboratory work has led to interest in applying the technology to environmental remediation and treatment of process waste streams. Work has appeared in the literature addressing issues related to the scale-up of the process and resolution of engineering problems.

2.4. I Reactor and System Design

A number of papers have addressed topics relevant to the designing of reactors for photocatalytic processes: 21, 22, 33, 35, 40, 69, 101, 108, 109, 191, g239, 261, g270, 275, 276, 277, 310, 370, 373, 472, 478, 502, 503, 548, g549, 553, 554, 568, 573, 585, 589, 591, 614, 640, and 647.

2.4.2 Systems Analysis

As the technology for photocatalyticly treating contaminated air or water has progressed, a few studies have compared the costs of solar energy and electric lamps as photon sources, others have compared the

photocatalytic processes with conventional treatment methods, such as carbon adsorption or UV-peroxide oxidation: 64,434, g480, 485, 508, 511,526, 584, 585, 586, and 662.

2.5 Miscellaneous Topics

This category includes papers of interest that do not fall into the preceding headings: photoelectrophoresis 81; photoelectrochemical detector 87; polypyrole formation 157; pigments 172; rate limiting processes 173, 174, 175; flat-band potentials 106; action spectrum 133; desorption of water 339, photoconductivity 460; laser photolysis 488, charge carrier dynamics 513; particle photoelectrodes 529,531; and UV attenuation 543.

2.6 Patents

The number of patents that cover aspects of photocatalytic technology has increased rapidly in the last decade. They cover a range of aqueous and gas-phase applications. Many are broadly written and appear to overlap in claims.

2.6. I Aqueous Systems

Patents that mainly focus on aqueous treatment range from specific waste streams and reactor types to those making broad claims that cover major segments of potential markets for the technology. These are covered in the following references: removal of organic compounds from water 78, 198, 261, 284, 324, 548, and 650; reduction of metals 50, 284, and 593; decarboxylation of saturated carboxylic acids 51; reactors and treatment processes 20, 107, 108, 109, 191, 371, 372, 373, 502, and 503; drinking water disinfection 553; electroless coating 349 and 350; use of peroxides as oxidizing agents 320; dye modified titanium dioxide 183; metallized photocatalyst 90; and photoelectrochemical reactor 21 and 22.

2.6.2 Gas-Phase Systems

A number of patents refer specifically to applications of photocatalytic process to remove or alter organic compounds in the gas streams. These are included in the following: ethylene and other hydrocarbons 225, 651, and 652; other organic compounds including chlorofluorocarbons and fluorocarbons 239, 307, 322, 409, 482, 471, and 473; deodorizing air 241, 271, 274, 275, 276, 277, 573, and 589; ammonia

oxidation 367 and 368; oxidants for gas-phase reactions 471 and 473; and reactor and catalyst configurations 246 and 638.

2.6.3 General Patents

Some patents contains claims that may be broad enough to cover aqueous or gas-phase systems or cover aspects of photocatalytic processes that can apply to both types of systems: processes 13, 199, 481, 591, and 592; photocatalyst structures and production methods 165, 167, 196, 209, 236, 285, 355, and 554; and reactors 478.

3.0 Compounds Studied

A list of the compounds included in various lists of priority pollutants, air toxics, and the toxic release inventory compiled by the EPA' provides a convenient frame of reference for citing the application of photocatalysis to compound oxidation. Table 1 lists compounds in the EPA categories; Table 2 lists organic compounds that are not in EPA lists; and Table 3 covers both EPA listed and unlisted inorganic compounds. The inorganic compounds are arranged by element unless a significant number of citations referred to work on a specific ion or compound. Formulas of compounds, when given, are not in the standard format because the software used to prepare the tables did not support subscripts. A few broad categories are included in Table 2 that reflect new applications. These are bacteria/algae, coal, AOX or haloform precursors, and oil/petroleum. Again, the citation prefix "g" indicates a gas-phase study. The treatability of compounds not studied can in many cases be inferred from results for related compounds in the tables.

[1] "Notice of the Second Priority List of Hazardous Substances Commonly Found at Superfund Sites," *Environmental Reporter*, October 28, 1988, 1255-1260.

Table 1. Organic Compounds in EPA Lists of Priority Pollutants, Air Toxics, Or Toxic Release Inventory

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
1,1,1-Trichloroethane	CHCl2CH2Cl		Cl		227,g321,341,342,429
1,1,2,2-Tetrachloroethane	CHCl2CHCl2		Cl		341,342,492
1,1,2-Trichloroethane	CHCl2CH2Cl		Cl		341,342
1,1,2-Trichloro-1,2,2-trifluoroethane	CCl2FCClF2		Cl,F		341,342
1,1-Dichloroethane	CH3CHCl2		Cl		341,342
1,1-Dimethyl hydrazine	(CH3)2NNH2			N	
1,2,3-Trichloropropane	CH2ClCHClCH2Cl		Cl		
1,2,4-Trichlorobenzene	C6H3Cl3	arom	Cl		16,318
1,2,4-Trimethylbenzene	C6H3(CH3)3				
1,2-Butylene oxide	H2COCHCH2CH3				
1,2-Dibromoethane	BrCH2CH2Br		Br		407
1,2-Dibromo-3-chloropropane (DBCP)	CH2BrCHBrCH2Cl		Br,Cl		
1,2-Dichlorobenzene	C6H4Cl2	arom	Cl		318,492
1,2-Dichloroethane	ClCH2CH2Cl		Cl		341,342,358,428
1,2-Dichloroethylene	ClHC:CHCl	olef	Cl		492
1,2-Dichloropropane	CH3CHClCH2Cl		Cl		492
1,2-Dinitrotoluene	C6H3CH3(NO2)2	arom		N	
1,2-Diphenylhydrazine	C12H12N2	arom		N	
1,2-Trans-dichloroethene	C2H2Cl2	olef	Cl		
1,3,5-Trinitrobenzene	C6H3(NO2)3	arom		N	
1,3-Butadiene	H2C:CHHC:CH2	olef			g24
1,3-Dichlorobenzene	C6H4Cl	arom	Cl		318
1,3-Dichloropropene	CHCl:CHCH2Cl	olef	Cl		
1,4-dichlorobenzene	C6H4Cl2	arom	Cl		169,316,435
1,4-Dioxane	OCH2CH2OCH2CH2				
1-Amino-2-methylanthraquinone	C6H4[C(O)]2C6H2NH2CH3	arom			
1-Bromo-4-phenyoxy benzene	p-BrC6H4OC6H5	arom	Br		
2,2,4-Trimethylpentane	(CH3)3C5H9				g321
2,3,7,8-Tetrachlorodibenzo-p-dioxin	Cl 2H4Cl4O2	arom	Cl		175,16
2,4,5-Trichlorophenoxyacetic acid	C6H2Cl3OCH2CO2H	arom	Cl		46,522
2,4,5-TP acid (silvex)	Cl3C6H2OCH(CH3)COOH	arom	Cl		
2,4,5-Trichlorophenol	C6H2Cl3OH	arom	Cl		16,46,125,129
2,4,6-Trichlorophenol	C6H2Cl3OH	arom	Cl		10,125,578,621
2,4,6-Trinitrotoluene	CH3C6H2(NO2)3	arom			
2,4 Diaminoanisole	(NH2)2C6H3OCH3	arom		N	
2,4-Dichlorophenoxyacetic acid	Cl2C6H3OCH2COOH	arom	Cl		272
2,4-Diaminoanisole sulfate	(NH2)2C6H3OCH3.H2SO4	arom		N	
2,4-Dichlorophenol	Cl2C6H3OH	arom	Cl		10,12,14,16,301,340,565 578,621

Substance	Formula	Class	Halogen	Het. Atom	TiO2 Reference
2,4-Dimethylphenol	(CH3)2C6H3OH	arom			
2,4-Dinitrophenol	C6H3OH(NO2)2	arom		N	327
2,4-Dinitrotoluene	C6H3CH3(NO2)2	arom			
2,4-Toluene diamine	CH3(NH2)2C6H3	arom		N	
2,6,Dinitrotoluene	C6H3CH3(NO2)2	arom		N	
2,6-Xylidine	(CH3)2C6H3NH2	arom		N	
2-Acetylaminofluorene	CH3C(O)NHC6H3CH2C6H4	arom	F	N	
2-Aminoanthraquinone	C6H4(CO)2C6H3NH2	arom		N	
2-Butanone	CH3COCH2CH3	keto			
2-Chloroacetophenone	C6H5COCH2Cl	arom	Cl		
2-Chloroethyl vinyl ether	CH2ClCH2OCHCH2	olef	Cl		
2-Chlorophenol	C6H4OHCl	arom	Cl		95,126,235,358,361,363,577 321,441,578
2-Ethoxyethanol	H3CCH2OCH2CH2CH2OH				85
2-Methoxyethanol	MeOCH2CH2OH				321
2-Methylnaphthalene	Cl 0H7CH3	arom			
2-Nitrophenol	NO2C6H4OH	arom		N	372
2-Nitropropane	CH3CHNO2CH3			N	
2-Pentanone, 4-Methyl	CH3(CH2)2COCH3	keto			
2-Phenylphenol	C6H5C6H4OH	arom			
3,3'-Dichlorobenzidine	C6H3ClNH2C6H3ClNH2	arom	Cl	*N*	
3,3'-Dimethoxybenzidine	[C6H3(OCH3)NH2]2	arom		*N*	
3,3'-Dimethylbenzidine (o-Tolidine)'	[C6H3(CH3)NH2]2	arom		*N*	
4,4'-Dichlorodiphenyldichloroethylene	(ClC6H4)2CCCl2	arom	Cl		
4,4'-Diaminodiphenyl ether	NH29C6H4)2NH2	arom		N	
4,4'-Isopropylidenediphenol	(CH3)2C(C6H4OH)2	arom			
4,4'-Methylenebis(N,N-dimethyl) benzenamine	Cl 7H22N2	arom		N	
4,4'-Methylenedianiline	H2NC6H4CH2C6H4NH2	arom		N	
4,4'-Methylene-bis-(2-chloroaniline)	CH2(C6H4ClNH2)2	arom	Cl	N	
4,4'-Thiodianiline	C12H12N2S	arom		S,N	
4,6-Dinitro-o-cresol	CH3C6H2(NO2)2OH	arom		N	
4,6-Dintro-2-methylphenol	C7H6N2O5	arom		N	
4-Aminoazobenzene	C6H5NNC6H4NH2	arom		N	
4-Aminobiphenyl	C6H5C6H4NH2	arom		N	
4-Chloroaniline	ClC6H4NH2	arom	Cl		
4-Chlorophenyl phenyl ether	p-ClC6H4OC6H5	arom	Cl		
4-Dimethylaminoazobenzene	(CH3)2C6H3NH2	arom		N	
4-Methylphenol	p-CH3C6H4OH	arom			
4-Nitrobiphenyl	C6H5C6H4NO2	arom		N	
4-Nitrophenol	NO2C6H4OH	arom		N	123
5-Nitro-o-anisidine	NO2C6H3(NH2)(OCH3)	arom		N	
Acenaphthene	Cl 0H6(CH2)2	arom			233

Substance	Fonula	:lass	-talo-gen	iet. .tom	Ti02 Reference
Acenaphthylene	C12H8	ırom			
Acetaldehyde	CH3CHO				g241,g547,g573
Acetamide	CH3CNOH2			N	
Acetone	CH3COCH3	:eto			151,265,g321,358,g451,g472
Acetonitrile	CH3CN			N	
Acetophenone	CH3C(O)C6H5	:eto			
Acrolein	CH2CHCHO	ılef			
Acrylamide	CH2CHCONH2	ılef		N	
Acrylic acid	H2C:CHCOOH	ılef			
Acrylonitrile	H2C:CHCN	ılef		N	
Aldrin	Cl 2H8Cl6	ırom	Cl		
Allyl chloride	H2C=CHCH2Cl	ılef	Cl		
Aniline	C6H5NH2	ırom		N	1,351
Anthracene	C6H4(CH)2C6H4	ırom			
Aramite	(CH3)3CC6H4OCH2CH(CH3)-SO3C2H4Cl	ırom	Cl	S	
Atrazine	C18H14ClN5	ırom	Cl	N	95,101,327,397,437,440,446 441,444,445,655,658
Benzal chloride	C6H5CHCl2	ırom	Cl		
Benzamide	C6H5CONH2	ırom		N	335
Benzene	C6H6	ırom			161,162,163,269,304,351,587 g256,268,g321,321
Benzidine	NH2(C6H4)2NH2	ırom		N	
Benzoic acid	C6H5COOH	ırom			32,208,258,351 352,357,358,361,363,582
Benzoic trichloride	C6H5CCl3	ırom	Cl		
Benzoyl chloride	C6H5COCl	ırom	Cl		
Benzoyl peroxide	(C6H5CO)2O2	ırom			
Benzo(a)anthracene	C22H14	ırom			
Benzo(a)pyrene	C20H12	ırom			
Benzo(b)fluoranthene	C20H12	ırom			
Benzo(g,h,i) perylene .	C22H12	ırom			
Benzyl alcohol	C6H5CH2OH	ırom			92
Benzyl chloride	C6H5CH2Cl	ırom	Cl		
BHC (Benzenehexachloride)	C6H6Cl6	ırom	Cl		
Biphenyl	C6H5C6H5	ırom			
bis(2-Chloroethoxy)methane	CH2(2-ClC2H5O)2		Cl		
Bis(2-chloroethyl) ether	ClCH2CH2OCH2CH2Cl		Cl		492
Bis(2-chloro- 1 -methylethyl) ether	[ClCH2(CH3)CH]2O		Cl		
Bis(2-ethylhexyl) adipate	(C7H13)2C4H8(CO2)2				
Bis(2-ethylhexyl)phthalate	(C4H9CH(CH2))2OOC				
Bis(chloromethyl)ether	(CH2Cl)O(CH2Cl)		Cl		
Bromochloromethane	BrCH2Cl		Br,C		

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
Bromodichloromethane	CHCl2Br		Cl,Br		
Bromoethane	C2H5Br		Br		
Bromoform (Tribromomethane)	CHBr3		Br		492
Bromomethane (Methyl bromide)	CH3Br		Br		
Butyl acrylate	CH2:CHCOOC4H9	olef			
Butylbenzyl phthalate	C4H9OOCC6H4COOC7H7	arom			
Butyraldehyde	CH3(CH2)2CHO				g68,g451
Calcium cyanamide	NCNCa			N	
Caprolactam	CH2(CH2)4NHCO			N	
Captan (N-Trichloromethylmercapto-tetrahydrophthalimide)	C9H8Cl3NO2S	arom	Cl	N,S	
Carbaryl [1-Naphthalenol, methylcarbamate]	C10H7OOCNHCH3	arom		N	
Carbon disulfide	cs2			S	
Carbon tetrachloride	ccl4		Cl		43,227,234,302,406,428,492
Carbonyl sulfide	c o s				
Catechol	C6H4(OH)2	arom			34,379,571
Chloramben (Benzoic acid, 3-amino-2, 5-dichloro-)	C6H(CO2H)(NH2)Cl2	arom	Cl	N	
Chlordane	Cl 0H6Cl8		Cl		
Chloroacetic acid	CH2ClCOOH		Cl		52,100,228,293,428,555
Chlorobentene	C6H5Cl	arom	Cl		321,351,358,366,426,428
					492,385
Chlorobentilate (Benzeneacetic acid, 4-chloro-alpha-(4-chlorophenyl)-)	(C6H4Cl)2C(OH)COOC2H5	arom	Cl		
Chlorodibenzodioxins, various	C12O2H8-xClx	arom	Cl		16,441,443
Chlorodibenzofurans	Cl 2OH8-xClx	arom	Cl		
Chlorodibromomethane	ClBr2CH		Br,Cl		
Chlorodifiuoromethane .	CHCl F2		Cl,F		
Chloroethane	C2H5Cl		Cl		341,342
Chloroform	CHCl3		Cl		4,234,292,351,428,468,492
					40,42,227,g321,321,393,394
					395,396
Chloromethane	CH3Cl		Cl		
Chloromethyl methyl ether	C2H5ClO		Cl		
Chloroprene	H2C:CHCCl:CH2	olef	Cl		
Chlorothalonil (1,3-Benzendedicarbonitrile, 2,4,5,6-tetrachloro-)	C6Cl4(CN)2	arom		N	
Chrysene	C18H12	arom			
cis-1,2-Dichloroethylene	ClHC:CHCl	olef	Cl		
cis-1,3-Dichloropropene	CHCl:CHCH2Cl	olef	Cl		
o-,m-,p-Cresols	CH3C6H4OH	arom			572
Cumene	C6H5CH(CH3)2	arom			

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
Cumene hydroperoxide	C6H5C(CH3)2OOH	arom			
Cupferron (Benzeneamine, N-hydroxy-N-nitrose, ammonium salt)	C6H5N(NO)ONH4	arom		N	
Cyclohexane	C6H12				203,611,612
Cyclohexanone	C6H10O	keto			
Cyclonite (RDX)	(CH2)4(NNO2)4			N	
Decabromodiphenyl oxide	(C6Br5)2O	arom	Br		
Dialate [Carbamothioic acid, bis (1-methylethyl)-, S-(2,3-dichloro-2-propenyl) ester]	[(CH3)2CH]2NCOSCH2CClCHCl	arom	Cl	N,S	
Diaminotoluene (mixed isomers)	CH3C6H3(NH2)2	arom		N	
Diazomethane	CH2N2			N	
Dibenzofuran	Cl2H8O	arom			
Dibento(a,h)anthracene	C22H14	arom			
Dibromochloropropane	CH2BrCHBrCH2Cl		Br,Cl		
Dibutyl phthalate	C6H4(COOC4H9)2	arom			
Dichlorobenzene (mixed isomers)	C6H4Cl2	arom	Cl		8,583
Dichlorobromomethane	CHBrC12		Cl,Br		
Dichlorodifluoromethane	CCl2F2		Cl,F		
Dichlorvos (Phosphoric acid, 2-dichloroethenyl dimethyl ester)	(CH3O)2P(O)OCH:CCl2		Cl	P	
Dicofol ,4,4'-Dichloro-alpha-trichloro-methylbenzhydrol	Cl4H9Cl5O	arom	Cl		
Dieldrin/aldrin	C12H10OPCl6	arom	Cl	P	
Diepoxybutane	C4H6O2				
Diethanolamine	(HOCH2CH2)2NH			N	
Diethyl phthalate	C6H4(CO2C2H5)2	arom			397
Diethyl sulfate	(C2H5)2SO4			S	
Dimethyl aminoazobenzene	C6H5NNC6H4N(CH3)2	arom		N	
Dimethyl formamide (DMF)	HCON(CH3)2			N	321 ,g321
Dimethyl phthalate	C6H4(COOCH3)2	arom			
Dimethyl sulfate	(CH3)2SO4			S	
Dimethylcarbamyl chloride	(CH3)2NCOCl		Cl	N	
Disulfoton	(C2H5O)2P(S)SCH2CH2SCH2CH			P,S	
Di-n-butyl phthalate	C6H4(COOC4H9)2	arom			187
Di-n-octyl phthalate	C6H4(CO2)(n-C8H17)2	arom			
Di-(2-ethylhexy) phthalate (DEHP)	C6H4[COOCH2CH(C2H5)C4H9]2	arom			
Endosulfan	C9H6Cl603S	arom	Cl		
Endrin aldehyde/ endrin	(Cl2H8OCl6)	arom	Cl		
Epichlorohydrin	CH2OCHCH2Cl		Cl		
Ethyl acrylate	CH2:CHCOOC2H5				
Ethyl chloroformate	ClCOOC2H5		Cl		
Ethylbenzene	C6H5C2H5	arom			

Substance	Formula	Class	Halo-gen	Het. atom	TiO2 Reference
Ethylene	H2C:CH2	olef			g24,225,g414
Ethylene glycol	CH2OHCH2OH				
Ethylene oxide	CH2CH2O				
Ethylene thiourea	NHCH2CH2NHCS			N,S	
Ethyleneimine (Aziridine)	CH2NHCH2			N	
Fluometuron [Urea, N,N-dimethyl-N'-[3-(trifluoromethyl)phenyl]-]	Cl OH1 1 F3N2O	arom	F	N	
Fluoranthene	C16H10	arom			
Fluorene	C6H4CH2C6H4	from			
Fluorotrichloromethane	CCl3F		Cl,F		
Formaldehyde	HCHO				g451
Heptachlor/heptachlor epoxide	Cl 0H7Cl7	arom	Cl		
Heptane	CH3(CH2)5CH3				
Hexachlorobenzene	C6Cl6	arom	Cl		
Hexachlorobutadiene	Cl2C:CClCCl:CCl2	olef	Cl		
Hexachlorocyclopentadiene	C5Cl6	olef	Cl		
Hexachloroethane	Cl3CCCl3		Cl		
Hexachloronaphthalene	Cl 0H2Cl6	arom	Cl		
Hexamethylphosphoramide	[(N(CH3)2]3PO			P,N	
Hexamethylene-1 ,6-diisocyanate	OCN(CH2)6NCO			N	
Hexane	CH3(CH2)4CH3				514
Hydraquinone	C6H4(OH)2	arom			142,379,254,571
Indeno(1,2,3-cd)pyrene	C22H12	arom			
Isophorone	C(O)CHC(CH3)CH2C(CH3)2CH2				
Isopropyl alcohol	(CH3)2CHOH				g5,g6,g7,113,g114,138,200,358 151,412,514,532,605,185 290,413,419,604,610,623
Lindane (gamma-Benzenehexachloride]	C6H6Cl6	arom	Cl		492
Malachite Green	C23H25ClN2	arorr	Cl	N	238,474
Malathion	(CH3O)2P(S)SCH(COOC2H5)CH2			P,S	182
Maleic anhydride	HC:CHC(O)OC(O)	olef			
Maneb (Carbamodithioic acid, 1,2-ethanediylbis-,manganese complex)	(SSCNCH2CH2NHCSS)Mn			N,S	
Mechlorethamine	CH3N(CH2CH2Cl)2		Cl	N	
Melamine	H2NCNC(NH2)NC(NH2)N			N	
Methanol	CH3OH				77,g96,139,g325,352,358 363,410,536,151,311,321 400,419,464,g597,600,602
Methoxychlor	Cl3CCH(C6H4OCH3)2	irom	Cl		
Methyl acrylate	CH2:CHCOOCH3	olef			
Methyl butyl ketone	CH3COC4H9				
Methyl ethyl ketone	CH3COCH2CH3				
Methyl iodide	CH3I		I		

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
Methyl isobutyl ketone	CHCOCH3				
Methyl isocyanate	CH3NCO			N	
Methyl methacrylate	CH2:C(CH3)COOCH3	olef			
Methyl tert-butyl ether	(CH3)3COCH				g472
Methylene bromide	CH2Br2		Br		
Methylene chloride	CH2Cl2		Cl		230,358,428,492,563,565
					562,564
Methylenebis(phenylisocyanate) (MBI)	CH2(C6H4NCO)2	arom		N	
Methylhydrazine	CH3NHNH2			N	
Michler's ketone	CO[C6H4N(CH3)2]2	arom		N	
Mirex	C10Cl12		Cl		
Mustard gas	S(CH3CH2Cl)2		Cl	S	
m-Nitroaniline	NO2C6H4NH2	arom		N	
N,N-Dimethylaniline	C6H5N(CH3)2	arom		N	
Naphthalene	C1OH8	arom			361
Naphthylamine (alpha-, beta-)	C10H7NH2	arom		N	
Nitrilotriacetic acid	N(CH2COOH)3			N	
Nitrobenzene	C6H5NO2	arom		N	351,352,353,358,363,464
Nitrofen [Benzene, 2,4-dichloro-1-(4-nitrophenoxy)-]	C12H7Cl2NO3	arom	Cl	N	
Nitrogen mustard (2-Chloro-N-(2-chloroethyl)-N-methylethanamine)	(ClCH2CH2)2NCH3		Cl	N	
Nitroglycerin	CH2NO3CHNO3CH2NO3			N	
Nitrophenol	NO2C6H4OH	arom		N	36,123,352,432
n-Butyl alcohol	CH3(CH2)2CH2OH				139
n-Dioctyl phthalate	(C8H17OOC)2C6H4	arom			
N-Nitrosodiethylamine	C4H1 ON20			N	
N-Nitrosodimethylamine	(CH3)2N2O			N	
N-Nitrosodiphenylamine	(C6H5)2NNO	arom		N	
N-Nitrosodi-n-butylamine	ONN(n-C4H9)2			N	
N-Nitrosodi-n-propylamine	ONN(n-C3H7)2			N	
N-Nitrosomethylvinylamine	ONN(CH3)(C2H3)			N	
N-Nitrosomorpholine	ONNC4H8O			N	
N-Nitrosonomicotine				N	
N-Nitrosopiperidine	C5H1 ONHNO			N	
N-Nitroso-N-ethylurea	C(O)(NH2)N(NO)C2H5			N	
N-Nitroso-N-methylurea	C(O)(NH2)N(NO)(CH3)			N	
n-Pentane	CH3(CH2)3CH3				
Octachloronaphthalene	C10Cl8		Cl		
Octane	CH3(CH2)6CH3				
Oxirane	H2COCH2				
o-Anisidine	CH3OC6H4NH2	arom		N	
o-Anisidine hydrochloride	CH3OC6H4NH2.HCl	arom	Cl	N	

Substance	Formula	Class	Halo. gen	Het. Atom	Ti02 Reference
o-Nitroaniline	NO2C6H4NH2	arom		N	
o-Toluidine	CH3C6H4NH2	arom		N	
o-Toluidine hydrochloride	CH3C6H4NH2.HCl	arom	Cl		
Parathion (DNTP)	(C2H5O)2P(S)OC6H4NO2	arom		P,S	182
PCBs (Aroclor 1260,1254,1248, and1242	C12ClxH1 O-x	arom	Cl		20,321,443,645
Pentachlorobenzene	C6Cl5H	arom	Cl		
Pentachlorophenol	C6Cl5OH	arom	Cl		12,14,49,340,377,492,522 578
Peracetic acid	CH3COOOH				
Phenanthrene	C4H10	arom			233
Phenol	C6H5OH	arom			15,32,34,208,351,354,358 423,424,196,433,515 516,517,518,579,582 33,35,321,345,364,365,464 510,555,575,576,580,607 608,609,619,621
Phenol,2-methyl	CH3C6H4OH	arom			
Phosgene	COCl2		Cl		g63,g408
Phthalic anhydride	C6H4(CO)2O	arom			
Picric acid	C6H2(NO2)3OH	arom		N	
Polybrominatedbiphenyls	C12BrxH1 O-x	arom	Br,Cl		
Propane sultone	C3H6SO2			S	
Propionaldehyde	C2H5CHO				
Propiolactone, beta-	OCH2CH2CO				
Propoxur [Phenol, 2-(1 -methylethoxy)- methylcarbamate]	C11H15NO3	arom		N	
Propylene oxide	CH2OCHCH3				
Propylene (Propene)	CH3CH:CH2				g24,g25,g1 0,g657
Propyleneimine	CH3HCNHCH2			N	
Pyrene	C16H10	arom			
p-Anisidine	CH3OC6H4NH2	arom		N	
p-Chloro-m-cresol	C6H3CH3OHCl	arom	Cl		
p-Cresidine	CH3C6H3(NH2)OCH3	arom		N	
p-Nitrosodiphenylamine	(C6H5)2NNO	arom		N	
p-Phenylenediamine	C6H4(NH2)2	arom		N	
Quinoline	C9H7N	arom		N	
Quinone	C6H4O2	arom			34
Quintozene (Pentachloronitrobentene)	C6Cl5NO2	arom	Cl	N	
Safrole	C3H5C6H3O2CH2				
sec-Butyl alcohol	CH3CH2CHOHCH3				
Sevin (carbaryl)	Cl 0H7OOCNHCH3	arom			
Sodium Alizarinsulfonate	SO3C6H3(CO)2C6H2(OH)2Na	arom		N,S	238,474
Styrene	C6H5CH:CH2	arom			

Substance	Formula	Class	Halo. gen	Het. Atom	Ti02 Reference
Styrene oxide	C6H5CHOCH2	arom			
Terephthalic acid	C6H4(COOH)2	arom			
tert-Butyl alcohol	(CH3)3COH				151,419,g601
Tetrachloroethylene	Cl2C:CCl2	olef	Cl		gl 1,52,177,428,492,557,587
					227,521,566
Tetrachlorvinphos	Cl 0H0Cl4O4P	arom	Cl	P	
Tetrahydrofuran	CH2CH2CH2CH2O				
Thioacetamide	CH3CSNH2			S,N	
Thiourea	(NH2)2CS			S,N	
Toluene	C6H5CH3	arom			91,161,162,163,164,304,321
					g321,403,406,g547,g549
Toluene diisocyanate	CH3C6H3(NCO)2	arom		N	
Total xylenes	C6H4(CH3)2	arom			
Toxaphene	ClOHlOCl8	arom	Cl		
Triaziquone	C12H13N3O2	arom		N	
Trichlorfon	(CH3O)2P(O)CH(OH)CCl3		Cl	P	
Trichloroethylene	CHCl:CCl2	olef	Cl		4,g118,g120,g121,333,358
					428,429,469,g473,484,492
					557,606,g11,52,g63,66,67
					105,g119,g122,177,227,228
					239,321 ,g321,370,g408,g453
					g471,555,g628
Triethytamine	N(C2H5)3			N	
Trifluralin	F3C(NO2)2C6H2N(C3H7)2		F	N	
Trinitrophenylmethylnitramine	(NO2)3C6H2N(NO2)CH3	arom		N	
Tris(2,3-dibromopropyl) phosphate	(CH2BrCHBrCH2O)3PO		Br	P	
Urethane (ethyl carbamate)	CO(NH2)OC2H5			N	
Vinyl acetate	CH3COOCH:CH2	olef			
Vinyl bromide	CH2CHBr	olef	Br		
Vinyl chloride	CH2:CHCl	olef	Cl		
Vinylidene chloride	CH2:CCl2	olef	Cl		
Xylene (mixed isomers)	C6H4(CH3)2	arom			304,g451
Zineb	Zn(CS2NHCH2)2			S,N	

Table 2. Other Organic Compounds Treated by a Photocatalytic Process

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
1,1,1,2-Tetrachloroethane	Cl3CCH2Cl		Cl		343
1,1,1-Trifluoro-2,2,2-trichloroethane	F3CCCL3		F,Cl		492
1,1,1 -Trifluorobromochloroethane	C2HF3ClBr		F		43,45
1,1-difluoro-1,2,2-trichloroethane	ClF2CCHCl2		F,Cl		492
1,1-difluoro-1,2-dichloroethane	FCICCCIH2		F,Cl		492
1,1-Difluoroethylene	CH2CF2	olef	F		g414
1,3-Diphenylisobenzofuran	(C6H5)2C6H2OC6H4	arom			596
1 -Bromodecane	BrC1 OH21		Br		438
1 -Bromododecane	BrC12H25		Br		448
1-Butanol	CH3(CH2)3OH				g68
1-Dodecanol	CH3(CH2)11 OH				448
1-Hexene	C6H12	olef			g545
1-Propanol	1-C3H7OH				139,311,358,454
2,3- or 3,4-Difluorophenol	F2C6H3OH	arom	F		379
Tris-(2,4-dichlorophenoxy)ethylphosphite	C2H5P[OC6H3Cl2]3	arom	Cl	P	560
2,6-Dichlorophenol	C6H3Cl2OH	arom	Cl		10,125,565
2,7-Dichlorodibenzo-p-dioxin	Cl2C12H6O2	arom	Cl		443
2-, 3-, 4-Fluorophenol	FC6H4OH	arom	F		379
2-Chlorodibenzo-p-dioxin	ClC12H7O2	arom	Cl		443
2-Chloroethylmethylsulfide	ClCH2CH2SCH3		Cl	S	156
2,3- and 2,5-Dichlorophenol	Cl2C6H3OH	arom	Cl		578
2,5-Dinitrophenol	(NO2)2C6H3OH	arom	Cl	N	123
2,6-Dichloroindophenol	C8H2N(OH)Cl2	arom			83
2-Furoic Acid	(CH2)3CHOCO2H				402
2-Naphthol	Cl 0H7OH	arom			
3,3,3-Trifluoropropene	CH2CHCF3				g414
3,3'-Dichlorobiphenyl	(ClC6H4)2	arom	Cl		443
3,4-Chlorophenol	3,4-Cl2C6H3OH	arom	Cl		125,442
3-Chlorophenol	m-ClC6H4OH	arom	Cl		126,363,521,578
3-Chlorosalicylic acid	C7H5ClO3	arom	Cl		490,491,582
4-Chloro-3-nitro-benzotrifluoride	C6HCl(NO2)F3	arom	F,Cl	N	117
4-Chlorophenol	ClC6H4OH	arom	Cl		16,17,48,358,361,363,565 577,582,378,578,621
4-Nitrocatechol	(NO2)C6H3(OH)2	arom		N	
4-Nitrophenylethylphosphinate	(NO2)C6H4(C2H5)PO2	arom		N,P	182
4-Nitrophenylisopropylphosphinate		arom		N,P	182
4-nitrophenyldiethylphosphate		arom		N,P	181,182
4-Thiophenyl-1-butanol	C6H5S(CH2)4OH	arom		S	153

Substance	Formula	Class	Halogen	Het. Atom	TiO2 Reference
4-t-Butyltoluene	p-(t-C4H9)C6H4CH3				455,g455
4-Hydroxybenzyl Alcohol	p-HO(C6H4)CH2OH	arom			477
5-Fluorouracil	FC4H(NH)2(O)2		F		327
5-Hydroxypentanoic acid	HO(CH2)4CO2H				298
12-phenyldodecanesulfonate, Sodium S	C6H5(CH2)12SO3H	arom			646
Acenapthane	Cl OH1 6(CH2)2				233
Acetic Acid	CH3CO2H				50,58,60,100,291,296,297
					298,352,358,363,196,475
					495,514,295,61,151,264,633
					g659,g660
Acetophenone	CH3COC6H5	arom			162,163,200
Adipic acid	C5H11CO2H				208,258
p-alkylphenol (various)	R(C6H4)OH	arom			447
Allyl alcohol	C3H5OH				456
Alochlor					387
AOX or Haloform Precursors					190,537,538
Asulam					560
Azobenzenes (various)	XC6H4NNC6H4X	arom		N	140,141,237,380,381,536
Bacteria/Algae					p167,249,348,493,494,553
					567
Benzoquinone	C6H4O2				379,423
Benzyldodecyldimethylamonium chloride	(C6H5CH2)(C12H25)(CH3)2N,Cl	arom	Cl	N	211,222
Biomass					137
Biphthalate	(C6H4)(CO2H)CO2)(-1)	arom			
Butane	C4H10				
Butyl alcohol	n-C4H7OH				g451,455
Butadiene	CH2CHCHCH2				g24
Butyric acid	C3H7CO2H				179844,495
Carbon dioxide (reduction) .	co2				g28,g188,247,226,240,254
					280,384,483,g558
Carbon monoxide	CO				g6,g55,g63,g201,g558
Carbon tetrabromide	CBr4		Br		g9
Chlorofluorocarbons, various			F,C		g307,g308,321,g321,g409
					g482,g492
Chloral hydrate	Cl3CO(OH)2		Cl		556
Chloranil, o- and p-	C6Cl4O2		Cl		377
Chloroethylammonium chloride	ClH3N,Cl		Cl	N	292
Coal					197
Congo Red	C32H22O6N6S2Na2				474
Cresol violet		arom			299,474
Cyanuric acid	C3N3(OH)3			N	440
Cyclohexanedicarboxylic Acids	C6H10(CO2H)2				399
Cyclohexene	C6H10				19,203

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
Cyclohexene oxide	C6H10O				19,622
Cyclophosphamide	OPONHC3H6[N(C2H4Cl)2]			P,N	327
Cynnamyl alcohol	C6H4C2H2OH	arom			456
DDT	(ClC6H4)2CHCCl3	arom	Cl		74,492,522
Decalin	C10H18				203
Decanoic acid	C9H19CO2H				438
Decanol	HOC1 OH21				433
Desipramine	(C6H4)2(CH2)2N(CH2)3NHCH3				327
Dibromomethane	CH2Br2		Br		407
Dichloroacetic acid	Cl2CHCO2H		Cl		100,428
Dichloroacetyl Chloride	Cl2CHCOCl		Cl		g63,g408
Diphenylmethane	(C6H5)2CH2	arom			319
Diphenylsulfide	(C6H5)2S	arom		S	154
Dodecane	Cl 2H26				448
Dodecyl sulfate	[Cl 2H25)2SO4				438,220,448
Dodecylbenzenesulfonate	(C12H25)C6H4SO3)(-1)	arom		S	211.222646
Doxycycline					326
Eosin					386
Ethane	C2H6				g115,g146,g652
Ethanol	C2H5OH				1,139,352,358,363,497,623
					251,252,253,267,413,419
					436,454,623
Ethylacetate	CH3CO2C2H5				358
Ethylenediaminetetraacetic acid	(O2CCH2)4N2C2H4			N	159,309,321,327,464,492
Fenitrothion	C9H12NO5PS	arom		NSP	560
Fluorescein	C20H12O5	arom			356,361,474
Formic Acid	HCO2H				62,194,351,352,358,363
					274,634,2,59,67,101,151
					353,464,g657
Glycerol					321
Hexafluoropropene	CF2CFCF3		F		g414
Humic Acids					353
Hydrocarbons					257
Hydroxybenzoic acid (various)	HOC6H4(OH)CO2H	arom			357
Hydroxycarboxylic acids, alpha	RCH(OH)CO2H				192
Hydroxyethylcellulose					595
Isobutane	C4H10				g110,g146,g147,g148,g149
					g127,g102,g202,g651
Isobutanol	CH3CH(CH3)CH2OH				623
Isobutene	C4H8				g24,g25,g29,g102,g110,g149
Isobutyric Acid	CH3CH(CH3)CO2H				g547,g549
Isoprene	CH2C(CH3)CHCH2				g255
Isorsorbide dinitrate	C6O2H8(ONO2)2			N	327

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
L-Lysine	NH2(CH2)4CH(NH2)CO2H				420
Lactic acid	C3H6O3				245,626
Malonic Acid	CH2(CO2H)2				193
Methane	CH4				184
Methanethiol	CH3SH			5	g274,g547,g549,g573
Methyl orange	Na,O3SC6H4N2C6H4N(CH3)2	arom		N,S	238,86,88,362,474
Methyl viologen					43,44,129,398,405,527,534
Methylene blue	(CH3)2NC6H3NSC6H3N(CH3)2,C	arom	Cl	N,S	238,359,362,474
Methylvinylketone	CH3COC2H3				340,388
Monuron	ClC6H4NHCON(CH3)2	arom	Cl	N	466
m-Phenoxytoluene	m-C6H5O-C6H4CH3				70
Naphthol	Cl 0H7OH	arom			358
Nitrotoluene, various	NO2C6H4CH3	arom		N	321
Nonylphenolethoxylate	C9H17C6H4OC2H5	arom			211,214,219,220,447
Oil/Petroleum					198,485,486,487,650
Oxalic acid	C2O4H2				151,179,193
Pendimethalin					387
n-Pentyl amine	n-C5H11 NH2			N	327
Permethrin					210,215
Picoline	CH3C5H4N	arom		N	152
Piperidene	C5H10NH			N	327,328
Polyethoxylene Alkyl Ethers	R2(OC2H4)n				212
Polyethylene	(CH2CH2)n				417
Polyvinylalcohol	(C2H3OH)n				374
Proline	C4H8NCO2H			N	328
Prometon					440,445
Prometryn					440,445
Propionic acid	C2H5CO2H				344,495,151,61
Propyne	CH3CCH				g24,g29
Pyridine	C5H5N	arom		N	327,328,g558
Pyrocatechol	o-C6H4(OH)2	arom			423
Reactive Dyes					636
Red Dye 79		arom		N,S	333
Resorcinol	C6H6O2				
Rhodamine B					362
Rose Bengal					569
Salicylic acid	C7H6O3	arom			1,351,352,358,361,363
					430,582,208,170,353,362
					364,435,464
Simazine	(C2H5)Cl(NHC2H5)C3N3			N	440,445
Sodium chloroacetate	CH3CO2Na		Cl		
Sodium dodecylbenzene sulfonate	C12H25C6H4SO3Na	arom		S	213,216,217,219,259
Stilbene	C6H5CHCHC6H5	arom			g6

Substance	Formula	Class	Halo-gen	Het. Atom	TiO2 Reference
Sucrose	Cl 2H22O11				352,353,358
Tetrafluoroethylene	C2F4	olef	F		g414
Tetralin	C10H12				203
Tetramethylenediamine	NH2(CH2)4NH2			N	305
Tetrabutylammonium phosphate	[(n-C4H9)4N]4,PO4			P	327
Theophylline	C7H8N4O2.H2O	arom		N	328
Thioethers	RSR'			S	99
Thiobencarb					111
Thymine	C5H6N2O2	arom		N	418
Trichloroacetic acid	Cl3CCO2H		Cl		100,292,342,428
Trietazine				N	440,445
Triethanolamine	N(CH2CH2OH)3			N	305,309
Trihydroxybenzene	(HO)3C6H3	arom			423
Trimethylamine	(CH3)3N			N	547,g573
Trinitrophenol	(NO2)3C6H2OH				123
Triphenylacetic acid	(C6H5)3CCO2H	arom			297
Umbelliferone	C9H6O3	arom			352,353,358,361

Table 3. Inorganic Substances Included in EPA Lists of Hazardous Substances And/Or Treated by a Photocatalytic Process

Substance/Element	Formula/Symbol	TiO2 Reference
Actinides	Th,Pa,U,Np,Pu	168,284
Aluminum (fume or dust)	Al	
Aluminum oxide	41203	
Ammonia	NH3	94,262,327,382,509,603,637 104,367,368,461
Ammonium nitrate (soln)	NH4NO3	
Ammonium sulfate (soln)	(NH4)2SO4	
Antimony	Sb	
Arsenic	As	
Asbestos	Mg,Si	
Azide ion	N3(-)	337
Barium	Ba	
Berylium	Be	
Bismuth	Bi	244
Boron	B	
Cadmium	Cd	464,465
Chlorine	Cl	
Chlorine dioxide	ClO2	
Chromium	Cr	3,171,463,464,489,634,641
Cobalt	co	
Copper	cu	61,91,463,475,60,59,450 464
Cyanide and Complexes	CN(-1) and M(CN)x	54,158,159,218,338,375,450 462,470,643
Gold	Au	8,77,79,80,284,527,528,528
Halide ion	X(1-), X = F, Cl, Br, or I	129,143,207,200,278,598,594 144,201,374,476
Hydrazine	H2NNH2	
Iron	Fe	91
Lead	Pb	312,314,574
Manganese	Mn	91,329
Mercury	Hg	463,464,465,523,238,570
Molybdenum	Mo	
Nickel	Ni	91,463,464,465
Nitrates/nitrites	NO3(-1),NO2(-1)	231,232,376,412,461,639 462,624,625
Nitric Oxide	NO	94,230,240,303,455,635
Nitrogen	N2	242,243,433,510,512,535 541

Substance/Element	Formula/Symbol	Ti02 Reference
Oxalate ion	C2O4(2-)	127,134,342
Oxygen	02	g180
Ozone	03	g415,g422
Palladium	Pd	453
Phosphorus		128,223,300
Platinum	Pt	79,80,284,463,464,465
Radium	Ra	
Radon	Rn	
Rhodium	Rh	79,80
Selenium	Se	
Silicon	Si	38,131,436
Silver	Ag	38,289,290,412,416,419,443 463,464,465,495,506,507 517,518,519,600
Strontium	Sr	
Sulfate radical	SO4(1-)	539
Sulfite		41,201,642
Sulfur		41,47,347,g547,g549
Sulfur dioxide	so2	
Sulfuric acid	H2SO4	
Thallium	TI	
Thiocyanate	SCN(1-)	130,313
Thiosulfate	S2O3(2-)	75,76,158
Thorium	Th	
Tin	Sn	131
Tritium	H,(T)	
Tungsten	W	568
Vanadium	V	
Zinc	Zn	91
Water	H20	31,135,136,176,183,273,286 287,287,306,401,498 501,616,617,627,630,629

4.0 Conclusions

The level of activity in this field has grown at a rapid rate. Early work was directed primarily at developing methods for synthesis of oxygenated organic compounds, but the potential to develop new methods for solving environmental problems has been the primary driving force for work in this area during the last decade. The ability to use sunlight photons to power the photocatalytic process has opened new avenues of research and development in applications of solar technology. The increase in patent activity during the last five years indicates that a variety of applications for photocatalytic detoxification are possible.

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This is a bibliography of information in the open literature on work that has been done to date on the photocatalytic oxidation of compounds, principally organic compounds. The goal of the listing is removing hazardous compounds from water or air. It contains lists of substances and literature citations. The bibliography includes information obtained through the middle of 1993 and some selected references from the balance of that year.

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