

## Supplement 1. Safe Handling of Hazardous Substances

### Appendix 3-5 Fire / Explosion Hazards of Flammable Substances

“Safety Guidelines for Chemical Experiments, 4<sup>th</sup> Edition” by the Chemical Society of Japan, Maruzen (1999)

**Ignition Point:** Most of the values are experimental ones measured with a closed ignition-point measuring apparatus and \* values were given by an open ignition-point measuring apparatus.

**Vapor Specific Gravity:** Values are given by comparing the density of gas or vapor with that of air, taking the density of air with equivalent pressure as 1. Namely, when vapor specific gravity is less than 1, gas or vapor is lighter than air, whereas when it is larger than 1, it is heavier than air.

**Water-solubility:** Water-solubility is an important factor when selecting the appropriate fire-fighting method. If substances are water-insoluble, firefighting by water is difficult, because they float on the surface of water. “Insoluble” means the water-solubility is less than 10 g/100 mL, “hardly soluble” shows the solubility around 10-24 g/100 mL and “soluble” means the solubility more than 25g/100 mL. “Decomposition” means decomposition by the reaction with water.

**Caution for Firefighting:** “Foam firefighting” means firefighting by chemical foam or water foam and “Alcohol foam” by air foam against alcohol. “Flowing by water or foam firefighting means the situation in which firefighting is difficult, because substances with high boiling point raise the liquid temperature to a higher temperature than the boiling point of water upon the fire, which causes rapid boiling of water upon contacting water to flow and spatter flammable liquids to expand the fire.

Sub-stance	Igni-tion Point (°C)	Flash Point (°C)	Explosive Limit (vol %)		Vapor Specific Gravity (Air=1)	Boil-ing Point (°C)	Specific Gravity (H <sub>2</sub> O=1)	Water-solubility	Cautions for Firefighting
			Lower Limit	Upper Limit					
Acryl-aldehyde	<-26	220	2.8	31	1.9	53	0.8	Soluble	Water is ineffective. Alcohol foam
Ethyl acrylate	10*	372	1.4	14	3.5	99	0.9	Hardly	Water is ineffective. Alcohol foam
Methyl acrylate	-3*	468	2.8	25	3.0	80	1.0-	Insoluble	
Acrylo-nitrile	0*	481	3.0	17	1.8	78	0.8	Soluble	Water is ineffective. Alcohol foam

Adipic acid	196	420	(1.6)			373	1.4	Hardly	Alcohol foam (flow by water foam)
Ethyl nitrite	-35	90 (dec)	4.0	50	2.6	17	0.9	Insoluble	
Acetal	-21	230	1.6	10.4	4.1	102	0.8	Hardly	Water is ineffective. Alcohol foam
Acetylene	Gas	305	2.5	100	0.9	-84		Soluble	Close main valve.
Acetanilide	169*	530	(1.0)	4.7	305	1.21		Insoluble	
Acet- aldehyde	-39	175	4.0	60	1.5	20	0.8	Soluble	Water is ineffective. Alcohol foam
Aceto- nitrile	6*	524	3.0	16.0	1.4	82	0.8	Soluble	Water is ineffective. Alcohol foam
Aceto- phenone	77	570	(1.1)		4.1	202	1.0+	Insoluble	
Acetone	-20	465	2.15	13	2.0	56	0.8	Soluble	Water is ineffective. Alcohol foam
Aniline	70	615	1.3	11	3.2	185	1.0+	Hardly	Alcohol foam
Aniline HCl	193*				4.5	245	1.22	Soluble	
2-Amino- ethanol	85	410			2.1	171	1.0+	Soluble	Alcohol foam
Allylamine	-29	374	2.2	22	2.0	56~57	0.8	Soluble	Water is ineffective. Alcohol foam
Allyl alcohol	21	378	2.5	18.0	2.0	97	0.9	Soluble	Water is ineffective. Alcohol foam
Aldol	66*	250	(2.0)		3.0	79~80	1.1	Soluble	Alcohol foam
Benzoic Acid	121	570			4.2	250	1.27	Hardly	
Methyl	83				4.7	200	1.1	Insoluble	For firefighting by

benzoate									covering, water is OK.
Anthra-quinone	185				7.2	380	1.44	Insoluble	
Anthracene	121	540	0.6		6.2	342	1.24	Insoluble	
Ammonia	Gas	651	16	25	0.6	-33		Soluble	Close main valve.
Isobutane	Gas	460	1.8	8.4	2.0	-12		Hardly	Close main valve.
Isobutyl alcohol	28	415	1.7	10.6	2.6	108	0.8	Soluble	Water is ineffective. Alcohol foam
Isoprene	-54	395	1.5	8.9	2.4	34	0.7	Insoluble	
Isopentane	<-51	420	1.4	7.6		28	0.6	Insoluble	
Isopentyl alcohol	43	350	1.2	9.0	3.0	132	0.8	Hardly	Alcohol foam
Isophorone	84*	460	0.8	3.8		215	0.9	Hardly	
Carbon Monoxide	Gas	609	12.5	74	1.0	-192		Insoluble	Close main valve.
Ethanol	13	363	3.3	19	1.6	78	0.8	Soluble	Water is ineffective. Alcohol foam
Ethane	Gas	472	3.0	12.5	1.0	-89		Insoluble	Close main valve.
N-ethyl aniline	85*				4.2	206	1.0-	Insoluble	
Ethyl-amine (70% aq.)	<-18	385	3.5	14.0	1.6	17	0.8	Soluble	Water is ineffective. Alcohol foam
Ethyl vinyl ether	<-46	202	1.7	28	2.5	36	0.7	Insoluble	Water is ineffective. Alcohol foam
Ethyl-benzene	15	432	1.0	6.7	3.7	136	0.9	Insoluble	
Ethyl methyl ether	-37	190	(2.0)	10.1	2.1	7	0.7	Soluble	Water is ineffective. Alcohol foam
Ethyl methyl	-9	404	1.7	11.4	2.5	80	0.8	Soluble	Water is

ketone									ineffective. Alcohol foam
Ethylene	Gas	450	2.7	36.0	1.0	-104		Soluble	Close main valve.
Ethylene oxide	<-18	429	3.6	100	1.5	11	0.9	Soluble	Water is ineffective. Alcohol foam (Vapor explosive)
Ethylene glycol	111	398	3.2			198	1.1	Soluble	Alcohol foam (outflow by water or foam)
Acethyl chloride	4	390	(5.0)		2.7	51	1.1	Decomp.	Ban on using water, foam.
Isopropyl chloride	-32	593	2.8	10.7	2.7	35	0.9	Insoluble	
Ethyl chloride	-50	519	3.8	15.4	2.2	12	0.9	Insoluble	
Vinyl chloride	Gas	472	3.6	33.0	2.2	-14		Insoluble	Close main valve.
Butyl chloride	-9	240	1.8	10.1	3.2	79	0.9	Insoluble	
Propyl Chloride	<18	520	2.6	11.1	2.7	47	0.9	Insoluble	
Benzyl chloride	67	585	1.1		4.4	179	1.1	Insoluble	Water can be used for covering firefighting.
Benzoyl chloride	72				4.9	197	1.2	Decomp.	Decomp. by reaction with water
Pentyl chloride	13*	260	1.6	8.6	3.7	108	0.9	Insoluble	
Methyl chloride	Gas	632	8.1	17.4	1.8	-24		Hardly	Close main valve.
1-Octanol	81				4.5	195	0.8	Insoluble	
Octane	13	206	1.0	6.5	3.9	126	0.7	Insoluble	

Oleic acid	189	363				286	0.9	Insoluble	Outflow by water or foam firefighting
Diacetyl peroxide	(45*)				4.1		1.2	Hardly	Explosion by heating
Formic acid (90% aq.)	50	434	18	57	1.6	101	1.2	Soluble	Alcohol foam
Isopropyl formate	-6	485			3.0	67	0.9	Hardly	Water is ineffective. Alcohol foam
Ethyl formate	-20	455	2.8	16.0	2.6	54	0.9	Insoluble	Water is ineffective. Alcohol foam
Propyl formate	-3	455	(2.3)		3.0	82	0.9	Hardly	Water is ineffective. Alcohol foam
Methyl formate	-19	449	4.5	23	2.1	32	1.0-	Soluble	Water is ineffective. Alcohol foam
o-Xylene	32	463	1.0	6.0	3.7	144	0.9	Insoluble	
m-Xylene	27	527	1.1	7.0	3.7	139	0.9	Insoluble	
p-Xylene	27	528	1.1	7.0	3.7	138	0.9	Insoluble	
Cumene	36	424	0.9	6.5	4.1	152	0.9	Insoluble	
Glycerin	160	370				290	1.3	Soluble	Alcohol foam (outflow by water, foam firefighting)
o-Cresol	81	599	1.4		3.7	191	1.1	Insoluble	Water can be used for covering firefighting.
m-, p- Cresol	86	558	1.1	(1.4)		203-203	1.9	Insoluble	
Crotonaldehyde	13	232	2.1	15.5	2.4	105	0.9	Hardly	Water is ineffective. Alcohol foam
2-Chloro-	60	425	4.9	15.9	2.8	129	1.2	Soluble	Alcohol foam

ethanol									
Chloro-benzene	29	593	1.3	9.6	3.9	132	1.1	Insoluble	Water is ineffective. (Covering firefighting is OK)
Acetic acid (glacial)	39	463	4.0	19.9	2.1	118	1.0+	Soluble	Alcohol foam
Isobutyl acetate	18	421	1.3	10.5	4.0	116	0.9	Insoluble	Alcohol foam
Isopropyl acetate	2	460	1.8	8	3.5	90	0.9	Hardly	Water is ineffective. Alcohol foam
Isopentyl acetate	32				4.5	121	0.9	Hardly	Water is ineffective. Alcohol foam
Ethyl acetate	-4	426	2.0	11.5	3.0	77	0.9	Hardly	Water is ineffective. Alcohol foam
Vinyl acetate	-8	402	2.6	13.4	3.0	73	0.9	Hardly	Water is ineffective. Alcohol foam
Butyl acetate	22	425	1.7	7.6	4.0	126	0.9	Hardly	Water is ineffective. Alcohol foam
Propyl acetate	13	450	1.7	8	3.5	102	0.9	Hardly	Water is ineffective. Alcohol foam
Benzyl acetate	90	460				215	1.1	Hardly	Alcohol foam (outflow by water, foam firefighting)
Pentyl acetate	16	360	1.1	7.5	4.5	149	0.9	Hardly	Water is ineffective. Alcohol foam

Methyl acetate	-10	454	3.1	16	2.6	56	0.9	Soluble	Water is ineffective. Alcohol foam
Carbon oxysulfide (Carbonyl sulfide)	gas		12	29	2.1	-50			Close main valve
Cyanamide	141				1.5	260 (dec)	1.3	Soluble	
Hydrogen cyanide (96%)	-18	538	5.6	40.0	0.9	26		Soluble	Vapor is highly toxic
Diisopropyl ether	-28	443	1.4	7.9	3.5	69	0.7	Insoluble	Alcohol foam
Diethyl-amine	-23	312	1.8	10.1	2.5	57	0.7	Soluble	Water is ineffective. Alcohol foam
Diethyl ether	-45	160	1.9	36.0	2.6	34	0.7	Hardly	Water is ineffective. Alcohol foam
1,4-Dioxane	12	180	2.0	22	3.0	101	1.0+	Insoluble	Water is ineffective. Alcohol foam
Cyclo-butane	gas				1.9	12		Insoluble	Close main valve
Cyclo-Propane	gas	498	2.4	10.4	1.5	-33		Insoluble	Close main valve
Cyclo-Hexanol	68	300	(1.2)		3.5	161	1.0-	Hardly	Alcohol foam
Cyclo-hexanone	44	420	1.1	9.4	3.4	156	0.9	Hardly	Alcohol foam
Cyclo-hexane	-20	245	1.3	8	2.9	81	0.8	Insoluble	
Cyclo-hexylamine	31	293			3.4	135	0.9	Soluble	Water is ineffective. Alcohol foam

1,2-Dichloroethane	13	440	6.2	16	3.4	83	1.5	Insoluble	
cis-1,2-dichloroethylene	6	460	9.7	12.8	3.4	60	1.3	Insoluble	Water is ineffective. (covering firefighting is OK)
1,2-Dichloropropane	16	557	3.4	14.5	3.9	96	1.2	Insoluble	Water is ineffective. (covering firefighting is OK)
o-Dichlorobenzene	66	648	2.2	9.2	5.1	180	1.3	Insoluble	Water can be used for covering firefighting
p-Dichlorobenzene	66	(648)	(2.2)	(9.2)	5.1	174	1.5	Insoluble	Water can be used for covering firefighting
Divinyl Ether	<30	360	1.7	27	2.4	28	0.8	Insoluble	
Dimethylamine	gas	400	2.8	14.4	1.6	7		Soluble	Close main valve
Dimethyl Ether	gas	350	3.4	27.0	1.6	-24		Soluble	Close main valve
p-Cymene	47	436	0.7	5.6	4.6	177	0.9	Insoluble	
Ethyl Bromide	(<-20)	511	6.8	8.0	3.8	38	1.4	Insoluble	
Butyl bromide	18	265	2.6	6.6	4.7	101	1.3	Insoluble	Water is ineffective. (covering firefighting is OK)
Methyl bromide	Practically not ignite	537	10	15.0	3.3	4	1.7	Insoluble	
Diethyl Oxalate	76				5.0	186	1.1	Gradually decomp.	



Tartaric Acid	210*	425			5.2		1.76	Soluble	
Ethyl nitrate	10		4.0	(100)	3.1	88	1.1	Insoluble	Water is ineffective. (covering firefighting is OK)
d-Camphor	66	466	0.6	3.5	5.2	203	1.0-	Insoluble	
Hydrogen	gas	500	4.0	75	0.1	-253		Hardly	Close main valve
Styrene	32	490	1.1	6.1	3.6	145	0.9	Insoluble	
Stearic acid	196	395				386	0.8	Insoluble	Outflow by water, foam firefighting
Diethyl carbonate	25				4.1	126	1.0-	Insoluble	
Decane	46	210	0.8	5.4	4.9	174	0.7	Insoluble	
Tetrahydrofuran	-14	321	2	11.8	2.5	66	0.9	Soluble	Water is ineffective. Alcohol foam
Tetramethyllead	38		(1.8)		6.5	dec. >100°C	1.6	Insoluble	
Tetalin	71	385	0.8	5.0	4.6	208	1.0-	Insoluble	
Dodecane	74	203	0.6		5.9	216	0.8	Insoluble	
Triethylamine	-7*		1.2	8.0	3.5	89	0.7	Insoluble	Alcohol foam
Triethylene glycol	167*	357	0.9	9.2		288	1.1	Soluble	Alcohol foam (outflow by water foam firefighting)
1,3,5-Trioxane	45*	414	3.6	29		115 (sublime)		Hardly	Alcohol foam
Trimethylamine	gas	190	2.0	11.6	2.0	3		Soluble	Close main valve
o-Toluidine	85	482		(3.7)	3.7	200	1.0-	Insoluble	
p-Toluidine	87	482		(3.9)	3.7	200	1.0-	Insoluble	
Toluene	4	480	1.2	7.1	3.1	111	0.9	Insoluble	
Naphthalene	79	526	0.9	5.9	4.4	218	1.1	Insoluble	

1-Naphthyl amine	157					300	1.2	Insoluble	Outflow by water, foam firefighting
2-Naphthol	153				5.0	296	1.22	Insoluble	Outflow by water, foam firefighting
1,1-Dichloroethane	-6		5.6			57	1.2	Hardly	Water is ineffective (Covering firefighting is OK) Alcohol foam
Disulfur dichloride	118	234				138	1.7	Decomp.	Decomp. by reaction with water
1,1-Dichloroethylene (Vinylidene chloride)	-18	570	7.3	16.0	3.4	32	1.2	Insoluble	Water is ineffective (Covering firefighting is OK)
Nicotine	(>104)	244	0.7	4.0	5.6	247	1.0	Soluble	Alcohol (Outflow by water, foam firefighting)
Nitroethane	28	414	3.4		2.6	115	1.04	Hardly	Water is ineffective (Covering firefighting is OK) Alcohol foam, explosion by heating
Nitroglycerin	Explosion	270				216 (explosion)	1.6	Insoluble	explosion by heating
p-Nitrotoluene	106					238	1.3	Insoluble	Outflow by water, foam firefighting
1-Nitro-	164					304	1.3	Insoluble	Outflow by water,

naphthalene									foam firefighting
1-Nitropropane	36	421	2.2		3.1	131	1.0	Hardly	Alcohol foam, explosion by heating
2-Nitropropane	24	428	2.6	11.0	3.1	120	1.0-	Hardly	Alcohol Foam, explosion by heating
Nitrobenzene	88	482	1.8		4.3	211	1.2	Insoluble	Water can be used for covering firefighting
Nitromethane	35	418	7.3	(100)	2.1	101	1.1	Hardly	Water is ineffective. Alcohol foam
Carbon disulfide	-30	90	1.3	50.0	2.6	46	1.3	Insoluble	Water is ineffective. (Covering firefighting is OK)
Nonane	31	205	0.8	2.9	4.4	151	0.7	Insoluble	
Paraldehyde	36*	238	1.3		4.5	128	1.0-	Hardly	Water is ineffective. Alcohol foam
Paraformaldehyde	70	300	7.0	73				Hardly	Alcohol foam
Hydrazine	38	(270)	2.9	98	1.1	113	1.0+	Soluble	Vapor explosive
Hydroxylamine	129 (explosion)					70	1.2	Soluble	Explosion by heating
Hydroquinone	165	516				286	1.3	Insoluble	Alcohol foam (Outflow by water, foam firefighting)
Pyridine	20	482	1.8	12.4	2.7	115	1.0-	Soluble	Water is ineffective. Alcohol foam

Phenol	79	715	1.8	(3.2)	3.2	182	1.0+	Soluble	Alcohol foam
1,3-Butadiene	gas	429	2.0	12.0	1.9	11		Insoluble	Close main valve
1-Butanol	29	343	1.4	11.2	2.6	117	0.8	Soluble	Water is ineffective. Alcohol foam
2-Butanol	24	405	1.7	9.8	2.6	94	0.8	Soluble	Water is ineffective. Alcohol foam
Octyl butanoate	218.3*	386						Insoluble	Outflow by water, foam firefighting
Butane	gas	287	1.6	(8.5)	2.0	-1		Hardly	Close main valve
t-Butyl alcohol	11	478	2.4	8.0	2.6	83	0.8	Soluble	Water is ineffective. Alcohol foam
1-Butene	gas	385	1.6	10.0	1.9	-6		Insoluble	Close main valve
2-Butene (cis)	gas	325	1.7	9.0	1.9	4		Insoluble	Close main valve
2-Butene (trans)	gas	324	1.8	9.7	1.9	1		Insoluble	Close main valve
Furan	<0		2.3	14.3	2.3	32	0.9	Insoluble	
Furfuryl alcohol	75*	491	1.8	16.3	3.4	171	1.1	Soluble	
2-Furaldehyde	60	316	2.1	19.3	3.3	162	1.2	Hardly	Alcohol foam
1-Propanol	23	412	(2.1)	13.7	2.1	97	0.8	Soluble	Water is ineffective. Alcohol foam
2-Propanol	12	399	2.0	12.7	2.1	82	0.8	Soluble	Water is ineffective. Alcohol foam
Propane	gas	432	2.1	9.5	1.6	-42		Insoluble	Close main valve
1,2-Propanediol	99	371	2.6	12.5		188	1.0+	Soluble	Alcohol foam
Ethyl propionate	12	440	1.9	11	3.5	99	0.9	Insoluble	

Methyl propionate	-2	469	2.5	13	3.0	80	0.9	Insoluble	
Propylbenzene	30	450	0.8	6.0	4.1	159	0.9	Insoluble	
Propylene	gas	455	2.0	11.1	1.5	-47		Insoluble	Close main valve
Propylene oxide	-37	449	2.8	37.0	2.0	35	0.9	Soluble	Water is ineffective. Alcohol foam
1-Hexanol	63	(293)	(1.2)		3.5	158	0.8	Hardly	Alcohol foam
Hexane	-22	223	1.1	7.5	3.0	69	0.7	Insoluble	
Heptane	-4	204	1.05	6.7	3.5	98	0.7	Insoluble	
Benzyl alcohol	93	436				205	1.0+	Hardly	Alcohol foam (Outflow by water, foam firefighting)
Benzaldehyde	63	192	1.4	3.7		178	1.0+	Insoluble	Water can be used for covering firefighting
Benzene	-11	498	1.3	7.1	2.8	80	0.9	Insoluble	
1-Pentanol	33	300	1.2	10.0	3.0	138	0.8	Hardly	Alcohol foam
Pentane	<-40	260	1.5	7.8	2.5	36	0.6	Insoluble	
1-Pentene	-18*	275	1.5	8.7	2.4	30	0.7		Water is ineffective
Formaldehyde	gas	424	7.0	7.3	1.0	-19		Soluble	Close main valve
Formaldehyde dimethyl acetal	-18*	237			2.6	44	0.9	Soluble	Water is ineffective. Alcohol foam
Acetic anhydride	49	316	(2.0)	10.3	3.5	140	1.1	Soluble	Alcohol foam
Phthalic anhydride	152	570	1.7	10.5		285	1.5	Insoluble	Outflow by water, foam firefighting
Maleic anhydride	102	477	1.4	7.1	2.5	202	0.9	Hardly	Alcohol foam (Outflow by water, foam firefighting)

Methanol	11	385	6.0	36	1.1	65	0.8	Soluble	Water is ineffective. Alcohol foam
Methane	gas	537	5.0	15.0		-162	0.6	Insoluble	Close main valve
Methyl-amine	gas	430	4.9	20.7	1.0	-6		Soluble	Close main valve
Methyl-cyclo-hexane	-4	250	1.2	6.7	3.4	101	0.8	Insoluble	
Ethyl bytanoate	24	463			4.0	122	0.9	Insoluble	Alcohol foam
Methyl butanoate	14				3.5	102	0.9	Hardly	Water is ineffective. Alcohol foam
Dimethyl sulfide	<-18	206	2.2	19.7	2.1	37	0.8	Hardly	Water is ineffective.
Hydrogen sulfide	gas	260	4.0	44.0	1.2	-61		Soluble	Close main valve
Diethyl sulfate	104	436				dec. to give ethyl ether	1.2	Insoluble slightly decomp.	Alcohol foam (Outflow by water, foam firefighting)
Dimethyl sulfate	83*	188			4.4	188	1.3	Insoluble	Water can be used for covering firefighting
Phos-phorus (red)		(260)			4.3	281	2.3	Insoluble	Water can be used for covering firefighting
Tri-o-tolyl phosphate	225	385				410 (dec)	1.2	Insoluble	Outflow by water, foam firefighting
Resorcinol	127	608	1.4		3.80	281	1.28	Soluble	

Ignition points, flash points, and explosive limits are mainly cited from NEPA No. 325M, the "Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids" (1997).