Theoretical Determination of the Time of Useful Function (TUF) on Exposure to Combinations of Toxic Gases

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The term "TUC" (Time of Useful Consciousness) has been used to describe the time during which an individual may be able to help protect himself from pressure change following sudden decompression at altitude. A similar term has not been suggested in the case of sudden exposure of humans to rapidly developing, serious contamination of the breathable atmosphere by the products of combustion and pyrolysis in relatively closed spaces, resulting from fire. This paper suggests the use of the term "TUF" (Time of Useful Function) and makes an attempt to establish a TUF for human exposure to a selected mixture of contaminants, with emphasis on short exposures (less than five minutes) at relatively high concentrations.

FOR MANY YEARS the value of the term "TUC" (Time of Useful Consciousness) has been recognized in estimating the available time one has to help himself immediately following a rapid decompression at altitude. A similar term has not been generally used in the case of sudden exposure to rapidly developing, serious contamination of the breathable atmosphere resulting from fire and the products of combustion and pyrolysis in relatively closed spaces. It is suggested that the term "TUF" (Time of Useful Function) be adopted to indicate the time available for escape under such circumstances.

In many of the fires occurring throughout the nation numerous deaths have been attributed to "smoke inhalation" or "carbon monoxide poisoning." Corollary information is needed regarding the contaminants, other than carbon and CO, which make up the smoke causing the fatalities. In some instances, contaminants contained in the smoke could be more rapidly incapacitating or lethal than CO. Contaminants are physically classified as aerosols, dust, fogs, fumes, mists, smoke, gases, and vapors.[6] Physiologically, they are considered as asphyxiants, irritants, anesthetics or narcotics, systemic poisons, and particulate matter other than systemic poisons. The entire problem area is so broad that the present discussion will be limited to only a few selected examples of asphyxiants and irritants. Those selected are CO_2, CO, and HCN (all asphyxiants), and NH_3 (an irritant). Many of the common air contaminants appear to belong to more than one physiological class and are therefore difficult to classify. However, the classifications of the selected four appear clear-cut.

During any given fire in a habitable space, the TUF will depend upon a variety of factors. These include: the materials that are burning, their combustibility, temperatures, the supply of O_2, air currents, and fire retardant treatment of the burning materials. Each factor plays a role in the composition of the contaminants evolved, whether the evolution is due to combustion of materials or to pyrolysis. Among the contaminants commonly evolved are CO_2, CO, fluorine, chlorine, cyanide, ammonia, and nitrogen dioxide; these are classed as either asphyxiants or irritants.

Most of the data available in toxicological literature for exposures of less than five minutes are concerned with lethal doses of toxic gases. Notable exceptions are the data on CO, CO_2, and HCN, which discuss the symptomatology of various concentrations as a function of time and a given static concentration. However, in the fires under discussion, the concentrations of all contaminants start at zero, and the rate of buildup is dependent on the numerous factors mentioned above.

Much of the literature is also primarily concerned with the TLV (Threshold Limit Value) for 8-hour exposures[6] and for extremely long-term exposures, as in space cabin environments;[2] these values deal with permissible levels to avoid harm, rather than with lethal levels. Noticeably lacking is information on the time of useful function for very short exposures, particularly for mixtures of contaminants at various ratios to each other and at different ambient temperatures, in and near fires. Undoubtedly, higher environment temperatures intensify the effects of toxic gases, singly or in mixtures, and therefore reduce the time of useful function.

The next consideration in the estimation of the TUF is the mode of physiological action of each contaminant in a mixture. For example, CO, CO_2, and HCN are all asphyxiants[1,3,6,9] but each has a different mode of action. All exert their actions simultaneously and independently. Therefore, the problem is to ascertain which toxicant will act most rapidly to incapacitate the individual, while the others aid in reducing the TUF still further. This latter effect will be a function of the con-

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centration of each toxicant, its mechanism of action, respiratory minute volume, pulse rate and circulation time, environmental temperature, and psychological factors. The chart illustrated by Forbes et al.[4] for CO uptaken appears unique in toxicology in that it considers the change in blood concentration of CO as a function of air concentration, minute volume of respiratory ventilation, pulse rate, and exposure time. Similar charts should be developed for other gases capable of being taken up by blood.

COMPARISON OF MODES OF ACTION OF THE SELECTED GASES

In the asphyxiant category, CO_2 is the least dangerous, CO is more dangerous, and HCN is the most dangerous toxicant with regard to concentration and speed of action. The differences in modes of action are significant. CO_2 acts as a simple asphyxiant (through exclusion of O_2) and as a respiratory stimulant, subsequently becoming a respiratory depressant. To compare these three gases with each other, a relatively high concentration of CO_2 can be tolerated for a relatively long period of time when it is the only air contaminant, but the presence of other toxicants tends to intensity the effects of CO_2.

CO acts by tying up the hemoglobin to the exclusion of O_2 producing hypoxia in the tissues. Another resultant action of tying up the hemoglobin seldom mentioned in the literature is the exclusion from the blood of metabolic CO_2. This promotes tissue retention of CO_2, thus intensifying the hypoxic effect of CO poisoning, the earlier onset of respiratory stimulation and its sequel, depression, and the accompanying tissue acidosis. One of the common symptoms of acidosis is hyperpnea. In this case CO_2 cannot be considered a simple asphyxiant, since the effect of hyperpnea is independent of the level of CO_2 in the respired air. Naturally, high CO_2 levels in the respired air would tend to intensify the CO_2 effect.

HCN is probably the fastest-acting breathable poison known. The fastest collapse from cyanide gas on record is about 10 seconds,[7] which would be equivalent to one or two breaths. Cyanide does not combine appreciably with either the oxidized or reduced form of hemoglobin, although it will combine with the approximately 2 percent of methemoglobin normally present in the blood. The critical action of cyanide occurs in the cells by interfering primarily with the cytochrome oxidase system to block cellular respiration.[6] This action occurs in spite of adequate O_2 simultaneously in the cells. This is supported by the fact that the $\Delta p\ O_2$ between the arterial and venous blood is only one volume percent instead of the usual four to five volumes percent. Mild doses of cyanide stimulate respiration,[7] which tends to increase the intake of other contaminants. Thus, since all of these asphyxiants act by different mechanisms, they can and do all act simultaneously. The final consideration, then, becomes their relative concentrations in the air respired by the individual, plus the physiological and environmental factors mentioned above. One factor not previously mentioned is the production of an hypoxic atmosphere, due to fire, which in turn intensifies the effects of any and all asphyxiants present.

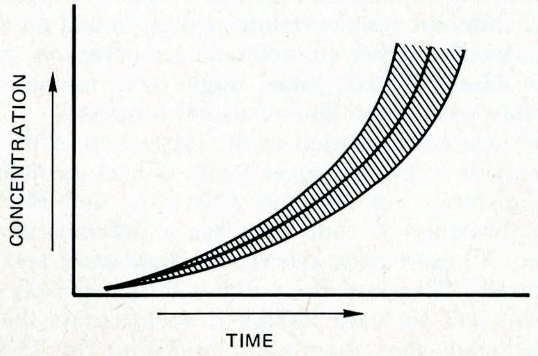

Fig. 1. Contaminant buildup.

Nitrogen dioxide is considered to be representative of most irritants. It is a lower-grade irritant than phosgene or fluorine, more irritating than ammonia, and near the midpoint of common pulmonary irritants. Irritants act primarily by causing corrosive action. The lung combats mild irritation by dilution, through the formation of fluid on the alveolar walls. In very high concentrations, irritants such as fluorine can destroy the capillary walls in the alveoli, causing hemorrhage.[5] In either case, the filling of the alveoli with serous fluid or blood causes a mechanical barrier to oxygenation and therefore becomes a mechanical asphyxiant.

In addition it contributes to incapacitation due to intrapulmonary hemorrhage. In high concentrations of severe irritants such as fluorine, both effects can occur very rapidly, within minutes. Another effect contributing to hypoxia and asphyxia is laryngeal and bronchial spasms caused by the inhaled irritants.

Ammonia is an irritant to mucous membranes, skin, and eyes; it is also absorbed through the mucosae, producing some systemic as well as local effects. The major damage, however, is caused by local damage to the nose, throat, bronchi, and lungs. The recommended TLV for ammonia was reduced recently (1968) from 100 parts per million (ppm) to 50 ppm,[8] indicating that its toxicity has been upgraded. Ammonia is a common contaminant in industrial environments, so frequently used that workers tend to become careless. One thousand ppm is considered intolerable, but half that figure, or 500 ppm, causes immediate irritation of eyes, nose, and throat.

How much is the TUF shortened by varying mixtures of these four toxicants? In the fire environment the individual is fortunate in one respect: the initial concentrations of these toxicants are zero. Therefore, there is a short period of grace before the concentrations become serious. The actual period of time, however, is highly dependent on the mix of environmental factors previously mentioned. Figure 1 illustrates the general pattern of contaminant buildup.

The next important factor is the qualitative composition of the gas mixtures evolving and the quantitative ratios of the component gases to each other. At this point the analysis must proceed on the basis of assumed compositions and ratios, unless actual qualitative and quantitative measurements are made.

Few controlled, instrumented, large-scale burn tests have been conducted. However, one series conducted in Cleveland by the AIA/ALPA group[10] was sufficiently controlled and instrumented to make possible a preliminary analysis of the results concerning the time of useful function. Two tests were conducted, and the summaries of the contaminant analysis are presented in Tables I and II. Test 2 (Table II) is taken for further analysis, since Test I data revealed conditions essentially safe for human inhabitance throughout the test.

In both burn tests, a partial list of contaminants measured included CO_2, CO, HCN, and NH_3, the four under consideration for this exercise. This provides some indication of contaminant levels possible in actual fires as a function of time, for a given set of circumstances. Because sets will vary widely, one can only assume a "worst case" set. At present, Test 2 provides the worst case of measured data.

TABLE I*. SUMMARY OF TOXIC GASES—AIA CLEVELAND TESTS
TEST NO. 1

	Lead 1		Lead 2		Lead 3			
Agent	PPM	%	PPM	%	PPM	%	Time in Test	Mechanism of Toxic Agent
NH_3	340	0.03	3,100	0.31	300	0.03	(End of	
CO_2	ND	—	8,000	0.80	8,000	0.80	Sample	NH_3—Lung irritant*
CO	ND	—	1,000	0.10	1,400	0.14	Period)	
HCN	ND	—	ND	—	ND	—		CO_2—Mild asphyxiant
HF	8	0.0008	5	0.0005	5	0.0005	3 Min 20 Sec	
Cum Total	348	0.03	12,105	1.200	9,705	0.97		
NH_3	740	0.074	2,240	0.224	630	0.063		CO—Asphyxiant
CO_2	8,000	0.80	14,000	1.400	8,000	0.80		HCN—Asphyxiant
CO	1,400	0.14	2,800	0.280	1,200	0.12	4 Min 35 Sec	(Cellular). Paralysis of
HCN	ND	—	ND	—	ND	—		respiratory center is im-
HF	11	0.0011	5	0.0005	7	0.0007		mediate cause of death
Cum Total	10,151	1.0151	19,045	1.9045	9,837	0.984		
NH_3	1,600	0.16	1,360	0.136	1,200	0.12		HF—Lung irritant[1]
CO_2	6,000	0.60	18,000	1.80	6,000	0.60		— — — — —
CO	800	0.08	3,200	0.32	1,000	0.10	6 Min 45 Sec	[1]Lung irritants produce
HCN	ND	—	ND	—	ND	—		pulmonary edema and
HF	13	0.0013	7	0.0007	12	0.0012		hemorrhage which serves as a mechanical asphyx-
Cum Total	7,413	0.74	22,567	2.26	8,212	0.82		iant
Lead Location	Pilot's Cockpit		Cabin Center Near-Ceiling		Cabin Center Seat Height			

*Data reprinted from "The Cleveland Aircraft Fire Test," by permission of the authors.[10]

TABLE II.* SUMMARY OF TOXIC GASES—AIA CLEVELAND TESTS
TEST NO. 2

	Lead 1		Lead 2		Lead 3			
Agent	PPM	%	PPM	%	PPM	%	Time in Test	Mechanism of Toxic Agent
NH_3	6,500	0.655	14,960	1.495	1,100	0.11	(End of	NH_3—Lung irritant*
CO_2	ND	—	8,000	0.80	4,000	0.40	Sample	
CO	320	0.032	48	0.0048	350	0.035	Period)	
HCN	2,500	0.25	300	0.030	2,900	0.29		CO_2—Mild asphyxiant
HF	7	0.0007	6	0.0006	7	0.0007	3 Min 20 Sec	
Cum Total	9,377	0.938	23,314	2.33	8,357	0.84		CO—Asphyxiant
NH_3	14,780	1.478	3,560	0.356	420	0.042		HCN—Asphyxiant
CO_2	14,000	1.40	36,000	3.60	8,000	0.80		(cellular). Paralysis of
CO	2,000	0.20	6,000	0.60	1,200	0.12	5 Min 20 Sec	respiratory center is im-
HCN	5,000	0.50	400	0.40	6,500	0.65		mediate cause of death
HF	10	0.0001	6	0.0006	7	0.0007		
Cum Total	35,790	3.58	45,966	4.597	16,127	1.613		
NH_3	13,650	1.365	4,100	0.41	2,250	0.225		HF—Lung irritant[1]
CO_2	38,000	3.80	92,000	9.2	80,000	8.0		— — — — —
CO	12,000	1.20	260,000	26.0	118,000	11.8	7 Min 42 Sec	[1]Lung irritants produce
HCN	11,000	1.10	200	0.02	43,000	4.3		pulmonary edema and
HF	10	0.001	8	0.0008	10	0.001		hemorrhage which serves as a mechanical asphyx-
Cum Total	74,660	7.466	356,308	35.63	243,260	24.33		iant
Lead Location	Pilot's Cockpit		Cabin Center Near-Ceiling		Cabin Center Seat Height			

*Data reprinted from "The Cleveland Aircraft Fire Test," by permission of the authors.[10]

APPROACH TO THE PROBLEM

If experiments were to be conducted on the time of useful function when breathing air containing a single contaminant gas, e.g., CO, an atmosphere containing a given static amount of CO would probably be used and administered by mask from a bottled, premixed supply. Assuming a constant pulmonary ventilation volume, this would provide a relatively linear increase in total CO breathed as a function of time. In a fire producing CO as a combustion product, the increase in total CO breathed versus time would not be linear. These differences can be shown by a conceptual, representative graph, as illustrated in Figure 2.

Figure 2 illustrates that the time available for useful performance is considerably longer (B) when breathing the fire-generated contaminant than when breathing a static, premixed gas mixture (A). This would vary, of course, with the assumed starting concentration of the latter example, but, in general, would be true except for very low levels of CO. It is also shown, as time and fire continue, that the total CO breathed will soon exceed that in the static mixture (C); after this point the static mixture becomes less hazardous to breathe. The difference in time from A to B is the grace period mentioned above in the actual fire situation, whereas time spent beyond C becomes more hazardous in the fire environment. Variations in the slope of either curve affect the TUF for that curve and change the period of grace. To obtain finite TUF's for CO, finite CO levels for both curves must be assumed.

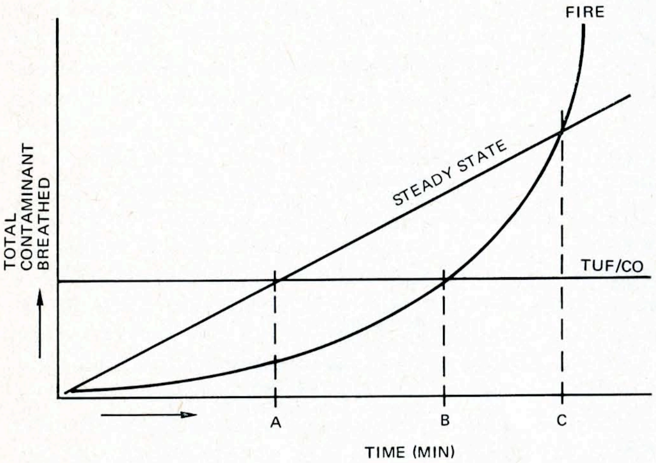

Fig. 2. Comparison of toxicants breathed: fire buildup vs. steady state mixture.

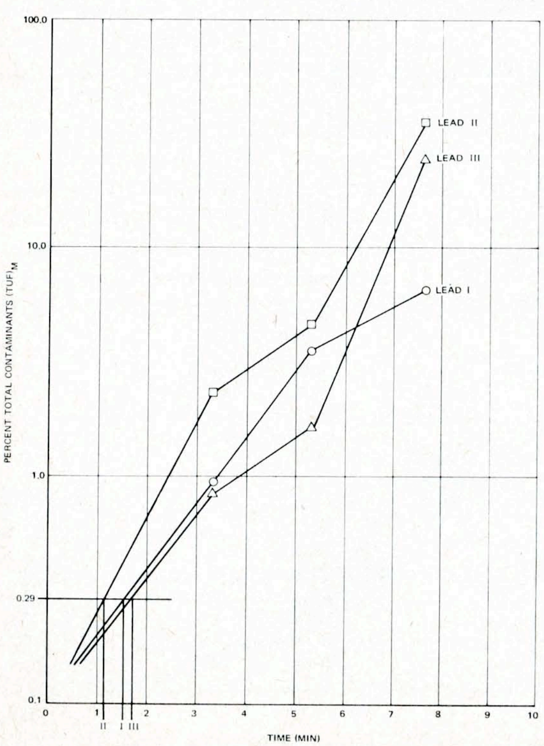

Fig. 3. AIA test No. 2 total contaminant buildup.

DISCUSSION

One possible method of approaching the mixed contaminant problem is to treat all four selected toxicants as a single asphyxiant. Ammonia, in a sense, can also be considered an asphyxiant because of the mechanical interference with alveloar gas exchange from edema and hemorrhage, and with respiration due to laryngeal and bronchial spasms.

In treating these four as a single asphyxiant, a ratio can be derived for the toxicity of the total atmosphere by arbitrarily selecting one gas as a standard. Considerable data are available for CO, which is the standard used here. The procedure is indicated as follows:

1. The lethal concentrations for 3-minute exposures (LC/3) are obtained for each of the four gases, HCN, CO, NH_3 and CO_2. These concentrations are 0.03, 1.28 percent, 0.5 percent, and 10.0 percent respectively.

2. These concentrations are added together and averaged. For this particular combination of gases, the total is 11.81 and the average is 2.95 percent.

3. CO is arbitrarily selected as a standard. The 3-minute lethal concentration $(LC/3)_{CO}$ is 1.28 percent; ratio is 0.43 (1.28/2.95).

4. A determination is made from standard data on symptoms produced by breathing given concentrations of CO for finite periods of time. An incapacitating concentration (ic/3) of CO when breathed for three minutes is judged to be 1.28/2 percent, or 0.64 percent for CO.

5. The (ic/3) of each toxicant is assumed to be 50 percent of the (LC/3), respectively. Therefore, the average of all the incapacitating concentrations $(ic/3)_m$ is 2.95/2, or 1.48.

6. $(TUF)_m$ is an index for the exposure concentration of an atmosphere containing these particular contaminants, significant for incapacitation. The $(TUF)_m$ in this case is 0.29 (0.43/1.48).

7. From the test data in Table II, the total concentration of the four contaminants is plotted against time (Figure 3), using semilog.

8. From Figure 3, the TUF is determined from the value for $(TUF)_m$ on the ordinate scale. In this case the TUF's are 1 minute, 30 seconds (Lead I), 1 minute,

10 seconds (Lead II), and 1 minute, 40 seconds (Lead III).

This relationship is expressed as follows:

$$(\mathrm{TUF})_m = \frac{(\mathrm{LC}/3)_{\mathrm{CO}}}{(\mathrm{LC}/3)_m\ (\mathrm{ic}/3)_m}$$

SUMMARY

A mathematical model has been presented for the determination of the Time of Useful Function (TUF), for purposes of escape from toxic atmospheres resulting from fire in habitable spaces, and which contain multiple toxicants of serious import. Little information is available in the literature concerning human tolerance to very short exposures (less than 5 minutes) to multiple contaminants at relatively high concentrations. Where information does exist for either single or multiple gases, lethality is usually the endpoint. For a TUF determination, the endpoint is the inability of the individual to escape from the hot, smoky environment, due to the inhalation of toxicants from combustion and pyrolysis. The TUF is analogous to the TUF associated with rapid or explosive decompressions.

REFERENCES

1. Armstrong, H. G.: Aerospace Medicine. Williams and Wilkins Co., Baltimore, 1961.
2. *Bioastronautics Data Book,* NASA SP-3006, Washington, D. C., 1964.
3. *Flight Surgeon's Manual,* Department of the Air Force, A. F. Manual 161-1, 1962.
4. Forbes, W. H., F. Sargent and F. J. W. Roughton: The rate of carbon monoxide uptake by normal man. *Am. Jour. Physiol.,* 143:594, 1945.
5. Lee, C-C: Metabolism and pharmacology of fluorine-containing compounds, Midwest Research Inst., Kansas City, Mo., AF Contract Report from AMRL (Aerospace Medical Research Labs) No. AMRL-TR-66-110, July 1966, USAF Contract No. AF33(615)-2472.
6. Patty, F. A.: *Industrial Hygiene and Toxicology.* 2nd Revised Edition, Volume I, 1958, and Volume II, Interscience Publishers, New York, 1963.
7. Sollmann, T.: *A Manual of Pharmacology.* 5th Edition, W. B. Saunders & Co., 1936.
8. "Threshold Limit Values of Airborne Contaminants for 1968—Recommended and Intended Values." American Conference of Governmental Industrial Hygienists, May 13, 1968.
9. *U. S. Naval Flight Surgeon's Manual,* Chief of Naval Operations and Bureau of Medicine and Surgery, Department of the Navy, 1968.
10. Heine, D. A., and J. J. Brenneman: The Cleveland aircraft fire test. AIA/ALPA, June 30 and July 1, 1966.