

CURRENT SUBMARINE CARBON MONOXIDE AND ESTIMATED CARBOXYHEMOGLOBIN
LEVELS AND INTERPRETATION OF THEIR POSSIBLE EFFECTS ON MENTAL PER-
FORMANCE AND HEALTH RISK

by

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SUMMARY PAGE

THE PROBLEM

Maximum permissible concentration of gaseous contaminants aboard submarines should be periodically reviewed in order to compare present ambient levels with recent scientific data collected relating a particular contaminant to health and performance. Carbon monoxide (CO) has received a great deal of attention in the civilian literature because non-smokers inhale this contaminant passively if they are in a closed or semi-closed environment. Although CO is removed by the ship's catalytic burners, a low level concentration still remains and thus submariners are chronically exposed to this contaminant. A survey of CO levels aboard 8 SSBN submarines during patrol was conducted and these values are presented in the report along with a discussion of the possible effects on health and performance.

FINDINGS

Carbon monoxide levels were as follows: patrol average (9 patrols of 8 submarines, average patrol length 53 days) = 7 parts per million (ppm); range = 4-10 ppm; average daily maximum = 9 ppm; mean of maximum recorded values = 13 ppm. Estimated carboxyhemoglobin (COHb) for the patrols was 1.53% (mean daily maximum = 1.71%; mean maximum value estimated = 2.23%).

APPLICATION

An analysis of the pertinent animal and human literature indicates that present CO levels and the estimated levels of COHb in the blood of non-smokers are below those concentrations which have definitely been shown to have deleterious effects on both mental performance and physical health. Not only are present levels below almost all safety standards for ambient, industrial, and military exposures, but the submarine atmosphere for this contaminant is cleaner than most major urban areas in warm weather. Conclusions drawn from these observations must be tempered with the following facts: Little is known about the additive, synergistic, or antagonistic effects of CO with agents such as other gaseous contaminants and common drugs. This survey was limited to 8 ships. Possible effects of low CO levels on smokers was not considered, nor were the possible long-term effects of repeated chronic exposures.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of Naval Medical Research and Development Command work unit - ZF51.524.006-1006 "(U) Carboxyhemoglobin (COHb) in smokers and non-smokers and ambient levels of nitrogen dioxide (NO₂) as a result of smoking during long patrols." The present report is No. 2 on this work unit. The manuscript was submitted for review on 30 October 1978, approved on 27 November 1978, and designated as Naval Submarine Medical Research Laboratory Report No. 883.

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ABSTRACT

Current carbon monoxide (CO) levels aboard nuclear powered submarines during patrol were examined by surveying 8 Atlantic fleet submarines (9 patrols). From hourly CO values obtained from the atmosphere control log, the following values were computed: patrol average = 7 parts per million (ppm); range = 4-10 ppm; average daily maximum value = 9 ppm; mean of maximum recorded values = 13 ppm. The hourly CO values were also entered into an equation developed to estimate percent carboxy-hemoglobin (COHb) in the blood of non-smokers. The mean estimated COHb for the 9 patrols was 1.53%, with fluctuations averaging $\pm 0.25\%$ and peaking during early morning hours. The mean daily maximum value was 1.71%, and the mean maximum value recorded was 2.23%. An analysis of the pertinent animal and human literature indicates that present CO levels and the estimated levels of COHb in the blood of non-smokers are below those concentrations which have definitely been shown to have deleterious effects on both mental performance and physical health. Conclusions drawn from these observations must be tempered with the following facts: Little is known about the additive, synergistic, or antagonistic effects of CO with agents such as other gaseous contaminants and common drugs. This survey was limited to 8 ships. Possible effects of low CO levels on smokers was not considered, nor were the possible long-term effects of repeated chronic exposures.

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Carbon Monoxide (CO)

A survey of carbon monoxide levels aboard fleet ballistic missile submarines during patrol was conducted by examining the daily "atmosphere control logs". Logs from eight Atlantic fleet ships were collected for patrols dating from August 1977 to March 1978. Hourly recorded CO values were entered into a PDP-11 computer, and the parameters in Table 1 were calculated. The patrol average for 8 ships (9 patrols) was 7 parts per million (ppm) and the range was 4-10 ppm. Data from an additional ship (Simon Bolivar) was collected during the winter of 1977 and reported separately (3). The average patrol CO for this ship was 7ppm. Deviations from the daily patrol mean were slight; the mean of the average daily maximum values for the 9 patrols was 9 ppm. The mean of the maximum values recorded for each patrol was 13 ppm.

Carboxyhemoglobin (COHb)

Exposure to elevated levels of CO will effect a rise in the carboxyhemoglobin concentration of blood. When CO can be precisely controlled at a given static level, such as in a laboratory setting, Coburn, et al (5) have formulated an equation to predict COHb concentrations in the blood for an ambient CO level. The relationship which has been verified by others, is

$$\text{COHb (\%)} = \alpha(\text{CO}) + \beta$$

where α is the exogenous level of CO, CO is given in ppm, and β is the endogenous level of CO. The coefficient α has been determined by a number of workers and is generally accepted by reviewers (6, 10, 13)

and government regulatory agencies (7) to be 0.16. While β , the amount of COHb formed in vivo due to endogenous production of CO can vary from individual to individual, 0.5 is the value cited in the federal air quality criteria for CO. Thus the equation:

$$\text{COHb (\%)} = 0.16 \text{ CO(ppm)} + 0.5$$

can be used to predict equilibrium COHb levels in blood under static CO conditions. From the work of Peterson and Stewart (11), it may be predicted that equilibrium values for COHb after exposure to constant low levels of CO (25 ppm and less) are not reached for some 12-24 hours. Thus use of the static equation should be applied only after appropriate exposure times.

In real life, such as that experienced aboard a nuclear submarine, ambient levels of CO are not steady but fluctuate on an hour to hour basis and to various degrees. Thus it is likely that COHb values never reach a true equilibrium under these conditions and are therefore always in a transient state. Ott and Mage (10) have incorporated the works of Coburn, et al (5), Peterson and Stewart (11), and Smith (12) in developing a dynamic model that will estimate the COHb concentration while CO is fluctuating. Their model uses the following equations:

$$\hat{y} = 0.0496 x_n + .669 \hat{y}_{n-1}$$

$$Y_n = \hat{y}_n + 0.5$$

$$(n = 1, 2, 3, \dots)$$

where y_n is the sum of both exogenous and endogenous COHb at any hour (n) and x_n is the given hourly value of ambient CO. \hat{y} is set at zero for initial conditions. This model assumes the following: 1) initial COHb value of 0.5 from endogenous production, 2) the coefficients are constant and the system being modeled is linear,

and 3) the individuals are engaged in constant light physical activity.

Application of the Ott-Mage model to the current submarine environment can thus provide a continuous estimate of blood COHb which depends not only on the present hourly reading but also on the history of all CO concentrations. Figure 1 shows a smooth plot of these computed hourly values for the two ships USS SSBN Lafayette and the USS SSBN Greene during the first 10 days of their patrols. There is an initial rapid rise from the assumed 0.5%¹ COHb at the start of the patrol to an average value of 1.8-1.9% with fluctuations of about 0.25% above and below this average. It is presumed that the number of CO catalytic burners (one or two) on line and the number of men smoking are the two main contributors to these fluctuations. A cyclical pattern is somewhat evident for the Lafayette. An analysis of the Lafayette's CO data for the first 10 days shows a cyclical pattern in the 8-hour moving average with peaks in concentration occurring during early morning hours and nadirs occurring in the afternoons. A similar pattern was observed for the Greene patrol. It is quite possible that the early morning peaks in the 8-hour average are related to the degree of leisure activity during the evening hours such as movie viewing, card playing, etc. and the fact that the greatest percentage of people are awake at this time.

The mean estimated COHb (dynamic model) for the 9 patrols was 1.53% (Table 2). The mean of the average daily maximum COHb% concentration for the 9 patrols was 1.7%, and the mean estimated maximum value was 2.23%. In this table, the average COHb concentration calculated from the static equilibrium equation [COHb% =

$0.16 \text{ CO}(\text{ppm}) + 0.5]$ is 1.64%. Interestingly, all the static values except one are greater than the patrol average computed using the dynamic model. Thus, under the special conditions aboard the closed environment of a submarine, it would appear that statically estimated COHb values would overestimate dynamically estimated COHb values by about 7%.

A thorough discussion of the principles involved in selecting a maximum permissible concentration (MPC) for CO in a closed environment over a long period of time was presented by Davies in 1975 (6). His excellent survey and analysis of the literature indicated that the MPC for a 90-day exposure should be reduced to 15 ppm from the then current U.S. and British limit of 25 ppm. Reducing the level from 25 ppm to 15 ppm would reduce the maximum allowable COHb in nonsmokers from 4.5% ($\text{CO} = .16 \times 25 + .5$) to 2.9% ($\text{CO} = .16 \times 15 + .5$). Decrements in vigilance and other cognitive tasks have been reported to occur below a COHb of 5%, but there was no evidence indicating that such function is compromised below 2.5% (6). Likewise, there was evidence from both animal and human experiments that COHb levels below 5% could have detrimental effects on physical performance or the long-term health outlook, while at 2.5% and below no such evidence could be found.

A review of the literature from 1975 to present continues to support a level of 2.5% COHb as that concentration where little, if any, decrement in physical or mental performance can be detected. By maximally exercising subjects on a treadmill and allowing them to breathe CO levels at 75 and 100 ppm, Horvath, et al (8) were able to demonstrate an impairment of maximal aerobic power and a reduction of time to exhaustion when COHb levels were 4.3%. No

such decrements were observed below the 4.3% level. A Russian group (9) has investigated the body's biochemical reaction to 30 days CO exposure of 13 and 18 ppm (estimated COHb: 2.6 and 3.4%) and a 90-day exposure to 9 ppm (estimated COHb: 1.9%). Significant increases in albumins and β -globulins, total lipids, cholesterol, β -lipoproteins and a significant decrease in blood sugar were observed during the higher 30-day exposures, but no such changes were observed for the long exposure at 9 ppm. In a recent vigilance performance study by Christensen, et al (4), subjects were exposed to three hypoxic producing situations: low O₂ (17%), 14 ppm CO, and a combination of 113 ppm CO and low O₂. The percent of signals detected during an alertness test was significantly decreased by low O₂, unchanged by CO exposure (measured COHb = 4.7%), and unchanged by a combination of low O₂ and increased CO. The latter observation indicates that CO was actually helpful in eliciting a compensatory mechanism to combat the low inspired O₂.

INTERPRETATION OF RISK OF PRESENT CO AND ESTIMATED COHb LEVELS TO HEALTH AND PERFORMANCE

An evaluation of the pertinent literature indicates that CO concentrations at or below 9 ppm and COHb levels at or below 2.5% will produce no discernible impairment to health, will not cause any acute or long-term health risk, and will not affect mental performance to such an extent that the efficiency of carrying out operational duties will be compromised. The survey of the 8 ships reported here shows that the average estimated COHb value (1.53%) is considerably below the 2.5% level, as is the average daily maximum level (1.7%). Of the 8 ships surveyed, representing

over 10,000 hourly data points, only on 2 ships were the maximum estimated COHb values greater than 2.5%. Further analysis of this data (Table 3) reveals that for all 9 patrols the CO exceeded 9 ppm only 16% of total patrol time and that the estimated COHb exceeded 2% only 10% of the total patrol time. Based on controlled laboratory studies, long-term exposure to low level CO during submarine patrols would seem to have no adverse effects on the crew.

SUBMARINE EXPOSURE VS OCCUPATIONAL AND PUBLIC EXPOSURES

An analysis of occupational exposures (3) and exposures of the public in and around large U.S. cities (7) indicates that submariners, as an occupational group, suffer the least exposure and are, in fact, subjected to lower levels of CO aboard a nuclear submarine than most city dwellers. Table 4 adapted from the works of Davies (6) and Stewart (13), clearly indicates that present on-board patrol CO levels are well within the standard set for most populations.

SUMMARY AND CONCLUSIONS

From the foregoing it is obvious that CO levels aboard nuclear submarines are below those concentrations which have definitely been shown to have deleterious effects on both mental performance and physical health. While such a conclusion is warranted from the evidence presented, it should be viewed with the following limiting qualifications. The survey included only 8 of the 41 nuclear missile submarines and only estimated COHb values for non-smokers were evaluated. Submariners who smoke have a 100 to 300% higher COHb than non-smokers. It would seem quite safe to assume that the added burden of low level CO inhalation during

the course of a patrol would have little effect on these crew members. This report has not discussed the possible additive, synergistic, or antagonistic roles which other agents may play in their interaction with CO. These agents could include any of the numerous other gaseous contaminants found aboard the closed recirculated environment of the submarine and may also include any of the common drugs such as aspirin, sedatives, tranquilizers, and antihistamines. There are virtually no reports in the literature that address these questions. The interpretation of the data collected for this report and the conclusions thus drawn assume that healthy, young men make up the exposed group. It is well recognized that the health of those persons who are susceptible because of respiratory or cardiovascular problems will be further compromised by exposure to low levels of CO. Aronow has shown that CO inhalation aggravates angina pectoris (1) and in his recent report shows this to be true even if subjects inhale CO passively from those smoking in a well-ventilated room (2). Davies (personal communication) also relates a severe reaction by two British subjects who were exposed to CO under experimental conditions because their cardiovascular limitations had not been previously diagnosed. Finally, little is known about repeated exposures over periods of from 1-20 years. The forecast of good health and performance for any given submarine CO exposure is good, but long-term extrapolation of this conclusion should be cautiously applied.

FOOTNOTE

1. Because of exposure to ambient CO while in port, this value is likely to range from 0.5% to 1.2% for any given individual.

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TABLE 1

CURRENT CARBON MONOXIDE LEVELS (ppm) DURING 9 FLEET BALLISTIC SUBMARINE PATROLS

Ship	Length of Patrol (Days)	Patrol Average	Average Daily Maximum	Maximum Value Recorded
Marshall	51	9	12	14
Rayburn	25	8	9	20
Rayburn	67	7	9	12
Lafayette	67	10	13	17
Greene	52	8	9	12
A. Jackson	41	4	4	5
Kamehameha	71	4	5	10
Hamilton	52	6	7	10
S. Jackson	51	8	10	14
MEAN	53	7	9	13

TABLE 2

ESTIMATED CARBOXYHEMOGLOBIN (COHb, %) LEVELS DURING 9 FLEET BALLISTIC MISSILE SUBMARINE PATROLS

SHIP	LENGTH OF PATROL (Days)	CO (ppm) PATROL AVERAGE	DYNAMIC [‡] COHb		DYNAMIC [‡] COHb AVERAGE DAILY MAX	DYNAMIC [‡] COHb MAX VALUE RECORDED
			STATIC* COHb PATROL AVERAGE	DYNAMIC [‡] COHb PATROL AVERAGE		
Marshall	51	9	1.94	1.86	2.10	2.43
Rayburn	25	8	1.78	1.64	1.83	3.11
Rayburn	67	7	1.62	1.92	1.70	2.28
Lafayette	67	10	2.10	1.63	2.21	2.65
Greene	52	8	1.78	1.48	1.80	2.21
A. Jackson	41	4	1.14	1.08	1.10	1.17
Kamehameha	71	4	1.14	1.03	1.20	1.92
Hamilton	52	6	1.46	1.45	1.56	1.94
S. Jackson	51	8	1.78	1.70	1.91	2.39
MEAN	53	7	1.64	1.53	1.71	2.23

* Static COHb patrol average estimated using COHb(%) = 0.16 CO (ppm) + 0.5
 ‡ Dynamic COHb estimated using Ott-Mage Model (see text)

TABLE 3

PERCENT OF TIME CO AND COHb EXCEED POSSIBLE THRESHOLD LEVELS

PATROL	LENGTH OF PATROL (Days)	% OF TIME CO EXCEEDS 9 ppm	% OF TIME COHb EXCEEDS 2%
Marshall	51	47	35
Rayburn	25	8	3
Rayburn	67	9	2
Lafayette	67	51	38
Greene	52	9	2
A. Jackson	41	0	0
Kamehameha	71	0	0
Hamilton	52	1	0
S. Jackson	51	23	14
MEAN	53	16	10

TABLE 4. COMPILATION OF PUBLIC, INDUSTRIAL, AND MILITARY CO EXPOSURE STANDARDS AND LIMITS

STANDARD/LIMIT (Reference)	CO CONCENTRATION (ppm)	COMMENTS
	<u>PUBLIC EXPOSURE</u>	
USA, Ambient Air, 8 hr (1)	9	Not to be exceeded more than once/yr Not to be exceeded more than once/yr "Warning" level for ambient air "Emergency" level for ambient air "Significant" harm to health "Significant" harm to health "Significant" harm to health Max Permissible concentration Max Permissible concentration for 24 hr average
USA, Ambient Air, 1 hr (1)	35	
USA, Ambient Air, 8 hr (2)	30	
USA, Ambient Air, 8 hr (2)	40	
USA, Ambient Air, 8 hr (2)	50	
USA, Ambient Air, 4 hr (2)	75	
USA, Ambient Air, 1 hr (2)	125	
USSR, Ambient Air, -- (3)	1	
FDR, Ambient Air, 8 hr (4)	8	
USA, Short Term Public Exposure (5)		
10 minutes	90	Exposures occurring at predictable times arising from single or occasionally repeated events
30 minutes	35	
60 minutes	25	
4-5 hr/day; 3-4 days/mo	15	
USA, Emergency Public Exposure (5)		
10 minutes	275	Exposures occurring at unpredictable times and places as the result of fire or accidents
30 minutes	100	
60 minutes	60	
	<u>INDUSTRIAL EXPOSURE</u>	
USA, Workroom, 8 hr (6)	50	OSHA: 8 hr time weighted average Allowable limit-based on air concen- tration that should not result in blood COHb levels above 10% Max allowable level. Assumes no CO in blood at beginning of exposure and a maximum allowable COHb of 14% threshold limit value threshold limit value
USA, Workroom, 8 hr (7)	50	
USA, (Pennsylvania) Workroom, 10 min (8)	1000	
USSR, Workroom (7)	18	
Czech, Workroom (7)	30	

MILITARY & SPACE EXPOSURES

USA, RN Submarines, 90 days (9)	15	Max permissible concentration for continuous exposure for 90 days
USA, Spacecraft, 90 days (10)	15	Max permissible concentration for continuous exposure for 90 days
USA, Spacecraft, 1000 days (10)	15	Max permissible concentration for continuous exposure for 1000 days

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ESTIMATED COHb LEVELS FOR NON-SMOKERS
DURING 1st TEN DAYS OF TWO PATROLS

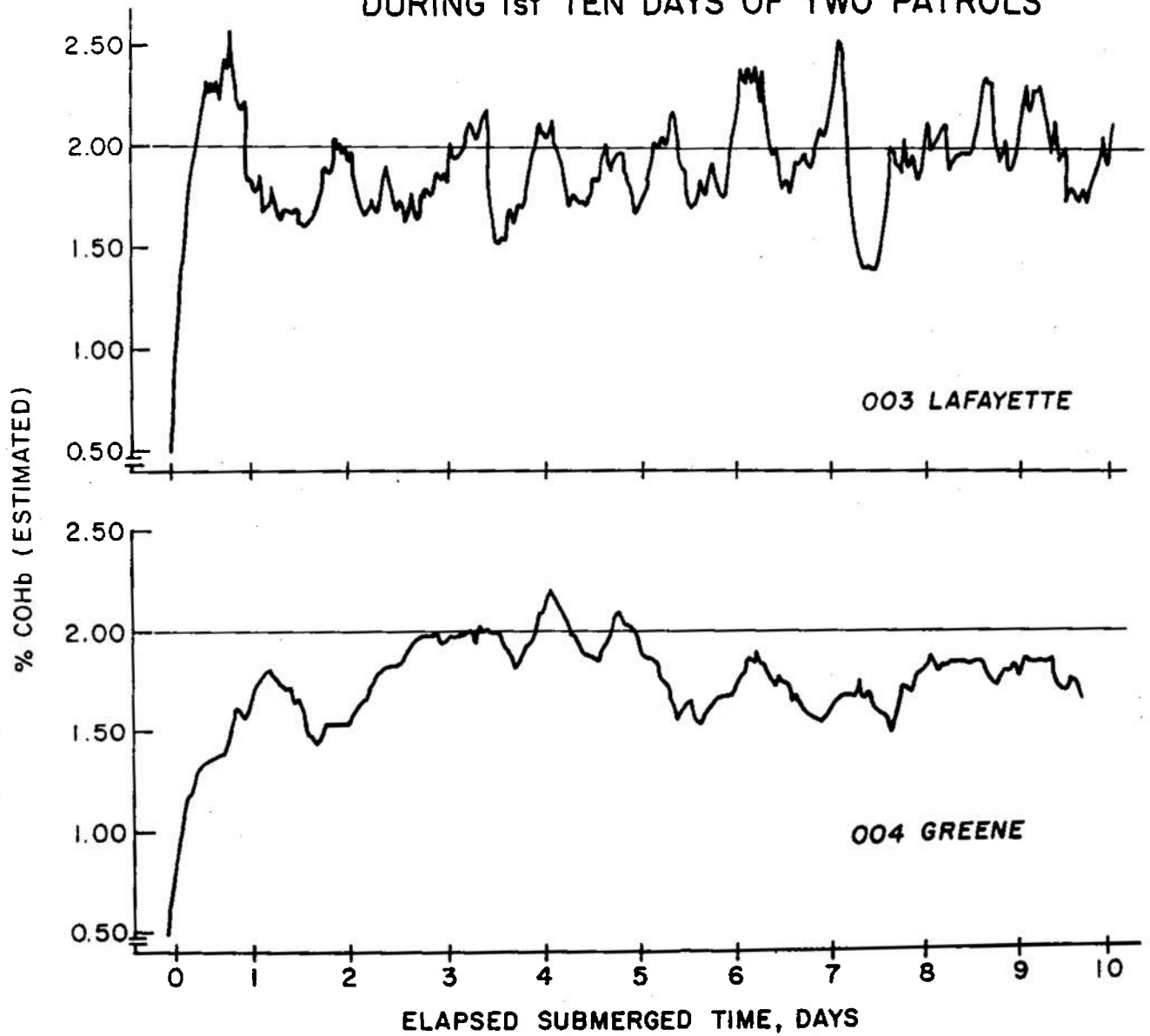


Figure 1. - Using a dynamic model and ambient hourly CO values obtained from ships' atmosphere control logs, COHb values in nonsmokers were estimated for the first ten days of two patrols. A line is drawn at 2% to give some orientation to a possible threshold value.

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averaging $\pm 0.25\%$ and peaking during early morning hours. The mean daily maximum value was 1.71%, and the mean maximum value recorded was 2.23%. An analysis of the pertinent animal and human literature indicates that present CO levels and the estimated levels of COHb in the blood of non-smokers are below those concentrations which have definitely been shown to have deleterious effects on both mental performance and physical health. Conclusions drawn from these observations must be tempered with the following facts: Little is known about the additive, synergistic, or antagonistic effects of CO with agents such as other gaseous contaminants and common drugs. This survey was limited to 8 ships. Possible effects of low CO levels on smokers was not considered, nor were the possible long-term effects of repeated chronic exposures.

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