REVIEW ARTICLE

Preventing carbon monoxide poisoning in the Hudson River Tunnel in 1921: recounting history

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ABSTRACT

The New York Bridge and Tunnel Commission began planning for a tunnel beneath the lower Hudson river to connect Manhattan to New Jersey in 1919. At 8,300 feet, it would be the longest tunnel for passenger vehicles in the world. A team of engineers and physiologists at the Yale University Bureau of Mines Experiment Station was tasked with calculating the ventilation requirements that would provide safety from exposure to automobile exhaust carbon monoxide (CO) while balancing the cost of providing ventilation. As the level of ambient CO which was comfortably tolerated was not precisely defined, they performed human exposures breathing from 100 to 1,000 ppm CO, first on themselves and subsequently on Yale medical students. Their findings continue to provide a basis for carbon monoxide alarm requirements a century later. ∎

1919-1921

Until the early 20th century the only way to cross the lower Hudson River from Manhattan in New York to New Jersey was by ferry. In 1919, planning began for construction of a motor vehicle tunnel beneath the Hudson River to connect Manhattan and Jersey City, New Jersey. The planned length of the tunnel was 8,300 feet, longer than any tunnel in use by motor vehicles in the world. In an 80-page appendix to the project status report to the New York Governor and Legislature in 1921, the New York Bridge and Tunnel Commission detailed its planning for ventilation of the tunnel [1]. At issue was the potential for carbon monoxide exposure from motor vehicle exhaust.

The planned Hudson River tunnel would surpass by far the 1,570-foot-long Rotherhithe Tunnel under the Thames River in London. It was to be constructed as two 29-foot diameter cast iron tubes, each providing space for two lanes of unidirectional traffic and a pedestrian sidewalk. The report notes that "not only healthy adults but also children and even invalids on their way to a hospital will be transported through it." Bridge traffic in New York at the time was described as "divided about evenly between horse drawn and motor vehicles," but it was wisely decided to plan for all motorized vehicular traffic. With this in mind, the builders recognized the potential for significant carbon monoxide accumulation from vehicle exhaust gas.

The Rotherhithe Tunnel in London used natural air flow for ventilation. Despite the passage of fewer than 100 cars per hour, "atmospheric conditions ... are bad, but there is no record of anyone having been overcome." The Hudson River tunnel was expected to come to maximum capacity shortly after opening, and the planners anticipated 1,900 vehicles per hour traveling through it.

Clifton M. Holland was the chief engineer on the project. He contracted with the U.S. Bureau of Mines to provide the engineers and physiologists necessary to perform studies to determine the maximal CO exposure allowable in the tunnel. Their problem was to determine a level of CO exposure that would be safe and to develop appropriate ventilation to achieve it. It was recognized that ventilation fans would be a major cost not only of initial tunnel construction, but also maintenance. Efficiency therefore dictated that the minimal safe ventilation possible be provided. Yandell Henderson from the Bureau of Mines was the physiologist in charge, and studies were carried out at the Yale University Bureau of Mines Experiment Station (Figure 1).

The team of investigators noted that the standards for safe carbon monoxide exposure had not been previously precisely defined. They described the work of the British scientist J.S. Haldane as having had dealt chiefly with the safety of miners after mine explosions and fires. Haldane's work attempted to define the level of CO exposure which would incapacitate or severely affect a man,

KEYWORDS: carbon monoxide; tunneling; ventilation; history

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DEPARTMENT OF THE INTERIOR, BUREAU OF MINES, F. G. COTTRELL, DIRECTOR

REPORT ON TUNNEL GAS INVESTIGATIONS TO THE CHIEF ENGINEER OF THE NEW YORK STATE BRIDGE AND TUNNEL COMMISSION AND THE NEW JERSEY INTERSTATE BRIDGE AND TUNNEL COMMISSION. PROBLEM NO. 2 PHYSIOLOGICAL EFFECTS OF EXHAUST GASES, YANDELL HENDERSON, PHYSIOLOGIST IN CHARGE.

OR

The Physiological Principles Applicable to the Ventilation of any Chamber, Tunnel, Mine, Fire Room, Garage, or Other Space in which the Air is Contaminated with Carbon Mono xide, and the Particular Application of these Principles to a Tunnel for Motor Vehicle s When the Time of Passage is Brief.— By Yandell Henderson, Howard W. Haggard, Merwyn C. Teague, Alexander L. Prince, and Ruth M. Wunderlich.

Figure 1

Title of Henderson's 80-page report on tunnel ventilation, which is actually an appendix to the 220-page 1921 report to the New York State Bridge and Tunnel Commission (reference 1). Figure in public domain, courtesy of HathiTrust, digitized by Google.

and not maximal amounts of CO that would be compatible with complete comfort and maximum efficiency. However, for the London Underground Railways, then drawn by coal-powered steam locomotives, Haldane had recommended a maximum CO concentration of 100 parts per million (ppm). When Haldane made that recommendation he was investigating the health of operating crews and assumed a duration of exposure adequate for complete equilibrium of CO with hemoglobin to occur.

The tunnel engineers did not adopt Haldane's standard. They felt that the ventilation required to achieve it would be impractical in an 8,300-foot-long enclosed space. It would be very expensive and associated with a wind velocity that would cause discomfort to passengers and potentially prove prohibitive of traffic movement.

As they began to address an upper limit for CO in the tunnel, the investigators first calculated human uptake of CO assuming an affinity of CO for hemoglobin to be 300 times that of oxygen and an alveolar oxygen concentration of 15%. At equilibrium, their estimates for carboxyhemoglobin (COHb) levels for exposures from 100 to 1,000 ppm are shown in Table 1.

They also noted that hours of exposure would be required to even approach equilibrium due to increasing back pressure from CO already absorbed. The maximal duration for tunnel transit under the Hudson River was predicted at 40 minutes. It was calculated that for a resting person breathing up to 700 ppm CO, the time required to reach one-half of equilibrium would always be at least one hour. They then chose to estimate that CO concentration which would allow "complete freedom from any trace of discomfort for healthy and vigorous adults exposed for periods of forty-five to sixty minutes." It was felt that this buffer would make tunnel transit safe for children and ill persons who might be more susceptible to CO.

Table 1

CO concentration (ppm)	Equilibrium carboxyhemoglobin level calculated
100	16.6%
200	28.5%
300	37.4%
400	44.4%
500	50.0%
600	54.5%
700	58.3%
800	61.5%
900	64.3%
1000	66.6%

Equilibrium carboxyhemoglobin levels calculated by tunnel engineers for humans exposed to CO at various concentrations (reference 1).

To determine this they constructed a 6-cubic-meter gas exposure chamber for human testing (Figure 2). Next, 15- to 60-minute exposures to CO concentrations of 200-1,000 ppm with serial blood samples to study kinetics of uptake and elimination were performed. The subject sat inside in a chair, read or performed minor tasks to simulate the level of activity of an automobile driver. Measured amounts of pure CO were infused through a port, mixed with an interior fan and the ambient CO concentration measured from gas samples drawn from another port. The chamber was equipped with a hole in the door through which the experimental subject could extend an arm for serial blood testing. While the study did examine COHb kinetics, it was primarily focused on symptoms.

Thirty-two experiments were performed on one female and nine male members of Henderson's staff. No one in 16 exposures had an appreciable headache after one hour breathing 200-400 ppm CO. A slight frontal headache was noted in two of nine subjects exposed to 600 ppm. Only six exposures were performed at levels greater than 600 ppm. Significant headache lasting four to eight hours was induced in four 800-ppm exposures, although it did not interfere with subsequent ability of the subjects to perform desk work. A single 900-ppm exposure caused a "decided frontal headache," irritability and insomnia. One 60-minute 1,000-ppm exposure was performed on Henderson himself. While he was described as "an unusually resistant subject," in this case he was "rather miserable and adverse to work for five or six hours and could still recognize the effects after twelve hours." He described a throbbing frontal headache and was noted to exhibit Cheyne-Stokes breathing. Corresponding COHb levels for the various exposures are shown in Table 2. It should be noted that Forbes exposed experimental subjects to CO breathing over the same concentration range 25 years later [2]. The COHb levels measured after 60 minutes of CO breathing during light activity were about 5% lower on average than those measured by Henderson, a difference attributed to changes in the measurement technique.

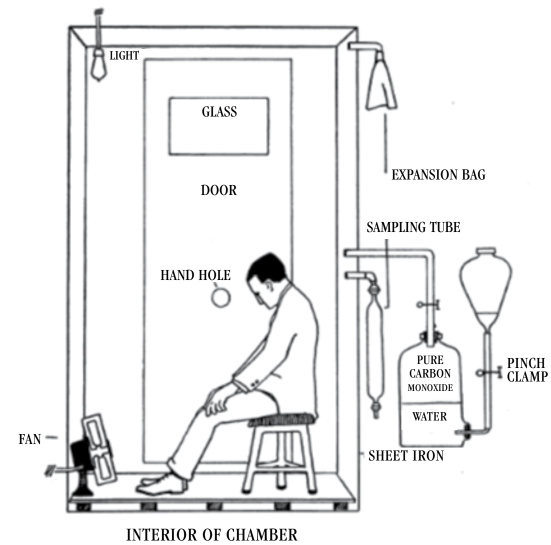

Figure 2
Schematic diagram of CO exposure chamber used by Henderson and co-workers in human testing (reference 1). Figure in public domain, courtesy of HathiTrust, digitized by Google.

Table 2

CO concentration (ppm)	Number of exposures	Carboxyhemoglobin (%)
200	2	11,12
300	3	10,13,14
400	11	12,14,14,17,18,20,21,22
500	1	--
600	9	16,16,16,17,18,18,21,25,26
800	4	22,24,24,27
900	1	34
1000	1	38

Blood carboxyhemoglobin levels measured after subjects breathed carbon monoxide for 60 minutes at varying concentrations in Henderson's exposure chamber (ref. 1).

To confirm their findings, Henderson's team constructed a second exposure chamber measuring 30 feet square with 12-foot walls. The 12,000 cubic foot (339 cubic meter) capacity represented the estimated volume a vehicle would occupy in the Hudson River tunnel when traffic was active. A Ford Model T automobile was placed inside and supported with blocks under the axles to raise the wheels off the ground (Figure 3). Groups of up to 12 Yale medical students stayed in the chamber for an hour with the vehicle's engine running. As long as 400 ppm was not exceeded, no appreciable ill effects were noted in any of the numerous subjects. Above this level, headache was noted in almost all cases and in some students, nausea and vomiting were also induced. As no person in either study developed symptoms breathing 400-ppm CO for one hour, that was defined as the upper permissible limit for the tunnel. Figure 4 summarizes the conclusions from the report. The engineers would design ventilation to allow a maximum

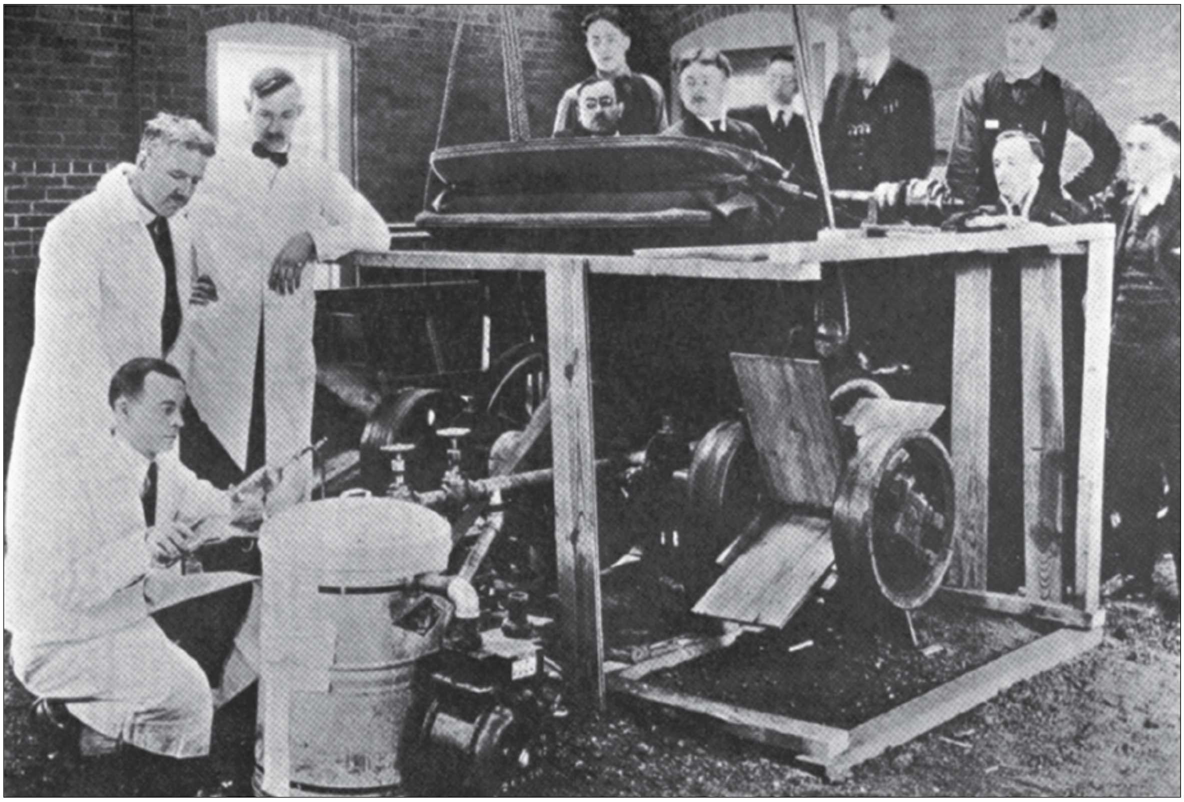

Figure 3

Inside the 340-cubic-meter exposure chamber showing engineers adjusting the Ford Model T automobile with blocks under its axles to allow operation at typical traveling speed. Groups of up 12 Yale medical students (eight shown here) remained in the chamber for one-hour-long CO exposures to assess symptoms (reference 1). Figure in Public domain, courtesy of HathiTrust, digitized by Google.

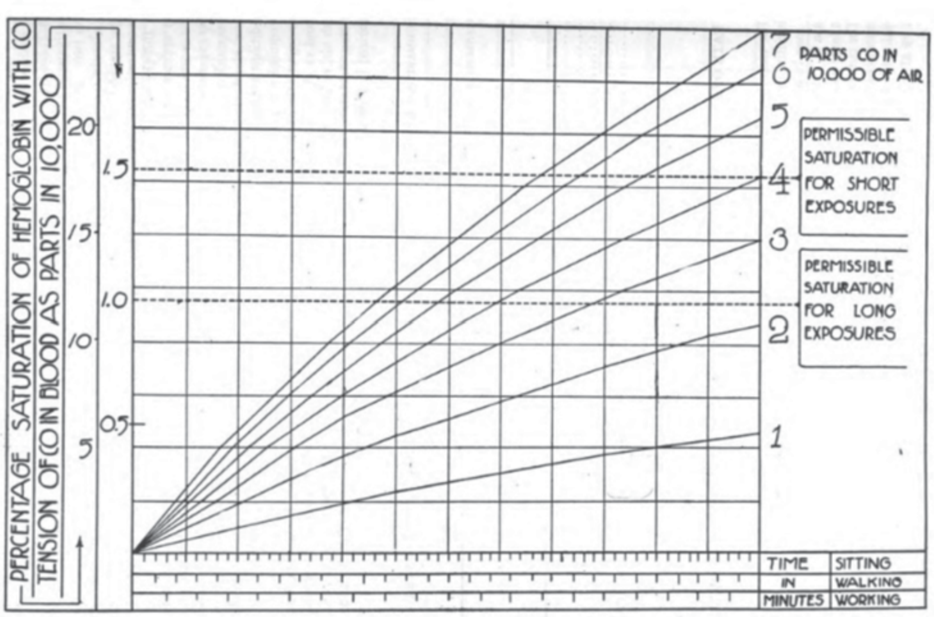

Figure 4

Summarized results of human CO exposures performed by Henderson (ref. 1). Figure in public domain, courtesy of HathiTrust, digitized by Google.

of 400 ppm in the tunnel. To do this, they invented a two-duct automatic ventilation system that would later be adopted by tunnel engineers around the globe.

The Next Century

Ground was broken on the tunnel construction in 1920, and it opened to the public in 1927. The Holland Tunnel under the Hudson River was named after the chief engineer on the project who tragically died from heart failure during construction in 1924.

The ventilation system required two ventilation buildings at each end of the tunnel. These buildings house a total of 84 massive fans: one-half of the fans pump clean air into the tunnel, and the other half serve as exhaust fans. Although only 56 of the 84 fans are operational at any time (the other 28 are reserved for emergencies), the system has the ability to completely exchange the air in the tunnel in just 90 seconds [3].

Sensors monitor the CO level in the tunnel 24 hours a day and adjust the fan speeds accordingly. On its first day of the tunnel operation in 1927, the average CO level was 69 ppm and the peak was 180 ppm, well below the 400-ppm limit. However, current levels are lower. In a 1990 study of CO exposure experienced by toll collectors and tunnel officers, the average level over an eight-hour shift was 8 ppm, with a range of 3-16 ppm and the average peak was 64 with a range of 27-131 ppm [4].

As noted, ventilation was planned for 1,900 vehicles per hour and a transit time of 45-60 minutes. Today more 100,000 vehicles pass through the tunnel daily, and a trip can take up to an hour. Despite a traffic volume more than twice anticipated, CO levels remain well controlled. This is likely related in part to the introduction of catalytic converters, which have been required in the United States on automobiles manufactured since 1975. From 1970 to 2019, total CO emissions from highway vehicles have decreased by approximately 90% [5], more than enough to compensate for a doubling of traffic passing through the tunnel.

Henderson's report had stated:

The whole matter may be even more simply summed up in a single expression involving the time measured in hours, the cocentration of carbon monoxide in air in parts per ten thousand and a constant for each degree of physiological effect. The physiological effect of all concentration and times (within reasonable limits) may be defined as follows:

(1) Time (hours) x concentration (parts per 10,000) = 3, no perceptible effects

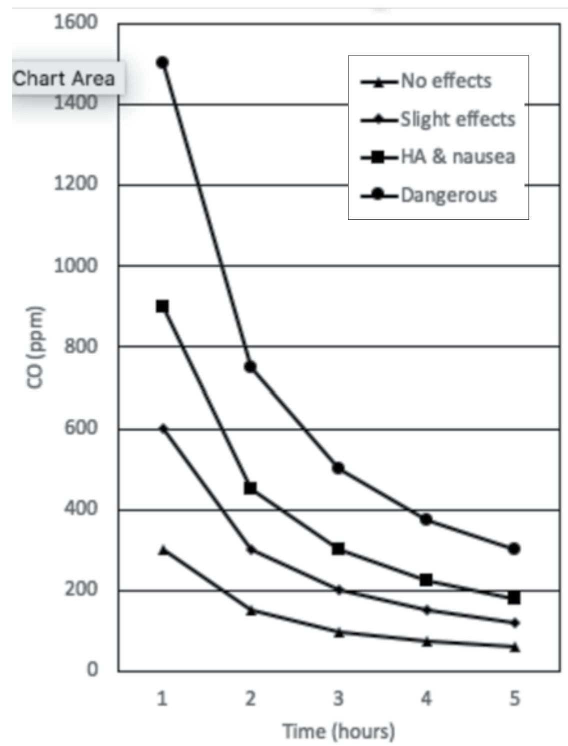

Figure 5

Curves generated by the author using Henderson's set of equations (reference 1) that predict likely physiological effects of increasingly severe CO exposures.

(2) Time (hours) x concentration (parts per 10,000) = 6, a just perceptible effect

(3) Time (hours) x concentration (parts per 10,000) = 9, headache and nausea

(4) Time (hours) x concentration (parts per 10,000) = 15, dangerous"

If the equations are used to calculate the CO concentrations necessary to achieve these physiologic effect points at one through five hours, the result is shown in Table 3 (CO in parts per ten thousand, as expressed by Henderson in his formula and time in hours). Converting CO to parts per million and graphing the data yields the curves seen in Figure 5.

Henderson could never have imagined how his work would be used over the next century. The following year in 1922, Brumbaugh and Jones of the National Bureau of Standards (NBS) published a technical paper on CO emissions from natural gas burners and reproduced Henderson's equations from the 1921 report, appropriately noting their origin [6].

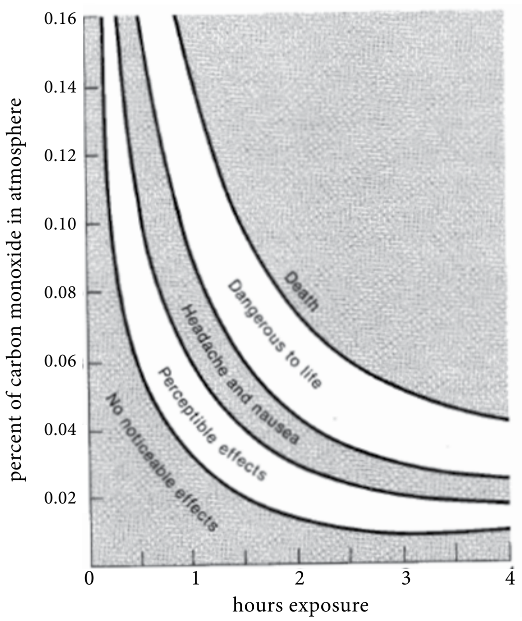

Figure 6a.

Chart showing CO ppm exposure levels and times resulting in progressively severe symptoms by Theines (reference 7).

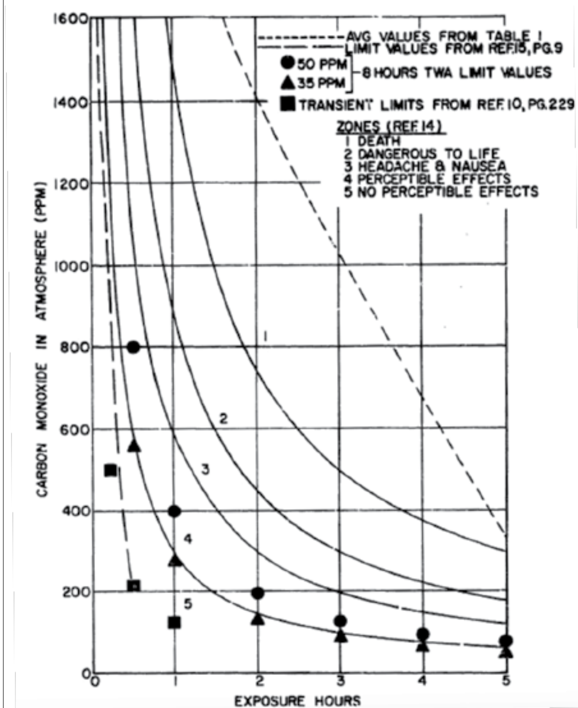

Figure 6b

Chart showing CO ppm exposure levels and time resulting in progressively severe symptoms (reference 8). Figure in public domain, approved by U.S. Army for public release with unlimited distribution.

Table 3

	physiological levels			
	3	**6**	**9**	**15**
1 hour	3.0	6.0	9.0	15.0
2 hours	1.5	3.0	4.5	7.5
3 hours	1.0	2.0	3.0	5.0
4 hours	0.75	1.5	2.25	3.75
5 hours	0.6	1.2	1.8	3.0

Carbon monoxide levels in parts per 10,000 that generate the physiological levels defined by Henderson as correlating with various symptoms at different time points (reference 1). See text for definition of physiological levels.

In a 1972 toxicology textbook chapter 50 years later [7], Thiens and Haley again reproduced Henderson's set of equations, citing the 1922 NBS technical report. Theirs was the first published graph depicting exposure curves which incorporated Henderson's equations (Figure 6a) [7].

Five years later Steinberg wrote a 1977 U.S. Army memorandum addressing human exposure to CO in military vehicles (combat vehicles and tanks) [8]. He had been tasked by the Army with identifying an upper limit for COHb that would not compromise soldier performance and chose 10%, based upon a literature review. His report included the chart seen in Figure 6b. As could be calculated from Henderson's set of four equations (Figure 5) and that drawn by Theines (Figure 6a), Steinberg's chart contains only four curves and references Henderson as its source.

At a subsequent unknown point in time, the graph became much more detailed. Shown in Figure 7 is the current version from the 2019 Edition of the National Fire Protection Association (NFPA) Code 72, "National Fire Alarm and Signaling Code" [9]. It includes 10 curves dividing the chart into 11 zones of progressively increasing degrees of CO exposure and the symptoms to be expected in each. The curves are labeled with COHb levels every 5% from 0-50%. No citation for the graph's origin is provided in the NFPA Code. The identical chart is also included in the Underwriters Laboratories (UL) 2034, "Standard for Single and Multiple Station Carbon Monoxide Alarms" [10]. In that instance a citation

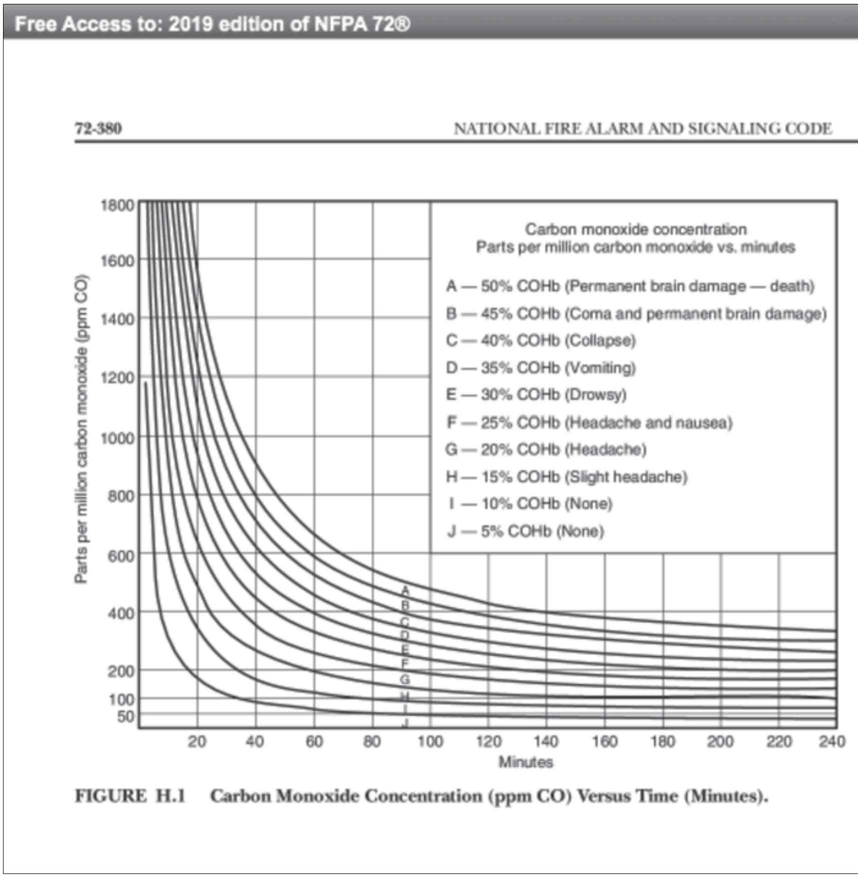

Figure 7

Chart showing CO exposure levels in ppm vs. time in minutes with resultant curves corresponding to various symptoms that will are to be expected (from reference 9, in Public Domain).

is provided on the relationship between inspired CO and COHb levels [11], but no support for the relationship to symptoms is given. This graph forms the basis for U.S. regulations requiring that carbon monoxide (CO) alarms alert after different durations of time, depending upon the concentration of CO present, with a goal of keeping COHb below 10% [10].

It has previously been demonstrated that carboxyhemoglobin levels correlate poorly with symptoms of CO poisoning [12,13]. Reasons proposed for this include blood sampling performed a variable amount of time after removal from CO exposure, interim supplemental oxygen administration, individual variation in response to CO, and the fact that many of the forms of toxicity from CO are not mediated through its effect on hemoglobin to reduce oxygen-carrying capacity of blood, as was believed by Henderson [1]. Other mechanisms of toxicity now known include binding to intracellular proteins such as myoglobin and cytochrome a,a3, resulting in impaired cellular energy production, nitric oxide generation increasing peroxynitrate production, lipid peroxidation by neutrophils, apoptosis, immune-mediated injury, and delayed inflammation [14].

It might be reasonably hypothesized that the level of CO and the duration of the exposure would correlate better with symptoms than COHb levels. However, neither of those variables is typically available with any accuracy in the clinical setting. Further, even when an ambient CO level is measured at the scene, it is a point in time and very likely changed during the exposure.

Empirical data do not exist to support the construction of Figure 7, despite its publication by the NFPA and UL. Doing such research today to differentiate the exposures required to cause the gradations of symptoms seen would certainly be considered unethical, on the basis of an unfavorable risk-benefit ratio [15]. It appears that someone used a commonly reproduced table of COHb levels vs. symptoms [16] and added detail to the original chart, increasing the number of zones from 4 to 11 and assigning specific symptoms to each zone. It should be remembered that Henderson's studies included only two CO exposures greater than 800 ppm, resulting in COHb levels of 34% and 38% (Table 2). He would probably be surprised to see his work on the Hudson River tunnel ventilation problem still used today but disappointed to see it embellished without data. The clinical data to support the particular symptoms resulting from these specific CO exposures don't exist and the implication that the relationships are absolute and documented to this degree of detail is unproven.

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Conflict of interest statement

The author declares that no conflict of interest exists with this submission.

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