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Carbon Monoxide Poisonings From Small, Gasoline-Powered, Internal Combustion Engines: Just What Is a "Well-ventilated Area"?

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This study modeled the time required for a gasoline-powered, 5 horsepower (hp), 4-cycle engine to generate carbon monoxide (CO) concentrations exceeding the National Institute for Occupational Safety and Health 200-ppm ceiling and 1200-ppm immediately dangerous to life and health concentration for various room sizes and ventilation rates. The model permitted the ambiguous term "well-ventilated area" to be defined. The model was compared with field data collected at a site where two workers were poisoned while operating a 5-hp concrete saw in a bathroom having open doors and an operating ventilation system. There is agreement between both the modeled and field-generated data, indicating that hazardous CO concentrations can develop within minutes. Comparison of field and modeling data showed the measured CO generation rate at approximately one-half of the value used in the model, which may be partially because the engine used in the field was not under load during data collection. The generation rate and room size from the actual poisoning was then used in the model. The model determined that ventilation rates of nearly 5000 ft^3/min (120 air changes per hour) would be required to prevent the CO concentration from exceeding the 200-ppm ceiling for short periods. Results suggest that small gasoline-powered engines should not be operated inside of buildings or in semienclosed spaces and that manufacturers of such tools should improve their warnings and develop engineering control options for better user protection.

Keywords: carbon monoxide, gasoline-powered engines, modeling, ventilation

M any workers have been poisoned in buildings or semienclosed spaces by carbon monoxide (CO) produced by small, gasoline-powered engines used on a variety of tools. Some products that are equipped with these engines have a warning stating that the product should be used only in "well-ventilated areas." However, many workers do not recognize the danger of using the tools in enclosed or semi-enclosed spaces, and poisonings occur quickly, even in the presence of what many would consider to be a well-ventilated area. Some victims, perhaps naively, have believed that an opened window or an operating fan define a well-ventilated area.

CO is a lethal poison that is produced when fuels such as gasoline are burned. It is one of many chemicals found in engine exhaust. Because CO is colorless, tasteless, odorless, and nonirritating, it can overcome the exposed person without warning. It produces weakness and confusion, sometimes depriving the person of the ability to escape the hazardous environment. CO poisons by binding tightly to hemoglobin in

the blood (forming carboxyhemoglobin), replacing oxygen, and reducing the oxygen-carrying capacity of the blood. CO also poisons by binding to tissues and cells of the human body and interfering with their normal function. Recognizing early warning signs of CO poisoning is sometimes difficult because early symptoms of CO exposure (headache, dizziness, and nausea) are nonspecific and may be mistaken for symptoms of other illnesses.

This article focuses on the concentration of CO in the environment as generated by a 5-horsepower (hp), gasoline-powered engine. It reviews the generation of CO during combustion, the occupational standards, and the methods of modeling and field data collection. It also defines "well-ventilated area" and compares the results of data collected in the field with the model.

BACKGROUND

Internal Combustion Engines

Internal combustion engines are designed to convert chemical energy from burning fuels into mechanical energy to perform work. To ensure the rapid burning required to power an engine, the gasoline must be vaporized and mixed with air in the carburetor. The introduction of a spark will cause the fuel-air mixture to flash almost instantly. The typical air-to-fuel weight ratio is 15 parts of air to 1 part of fuel; however, this ratio varies depending on operating conditions.[1]

CO is one of many undesirable by-products resulting from the incomplete combustion of organic material. Because combustion is usually incomplete, resulting from insufficient oxygen or the presence of impurities, CO is formed. The relative amounts of CO produced from gasoline-powered engines depend on engine design, operating conditions, and most importantly the fuel/air equivalence ratio.[2] The fuel/air equivalence ratio is the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. The composition of combustion products is significantly different for fuel-lean and fuel-rich mixtures. Rich fuel-air mixtures and high operating temperatures result in significant CO concentrations. Exhaust gases released from a gasoline engine may contain from 0.1 to 10% CO (1000 to 100,000 ppm). Engines operating at full-rated hp will produce exhaust gases having approximately 0.3% CO.[3]

Emissions and Exposures

A great deal of work has been done in the United States to determine the types of emissions produced from small, gasoline-powered engines and how those emissions can be reduced. One study of small, modern, two- and four-stroke engines found that CO emissions ranged from 0.17 ft³/min for a 0.8 hp, two-stroke, gasoline-powered engine to 3.28 ft³/min for an 18 hp, four-stroke, side-valve, gasoline-powered engine. A 4.5 hp, four-stroke, overhead valve, gasoline-powered engine on a walk-behind mower generated 0.98 ft³/min, and a 4.5 hp, four-stroke, overhead valve, propane-powered engine on a walk-behind mower generated 0.39 ft³/min.[4]

Much of the emission research has been spurred by environmental regulation, such as the California Air Resources Board (CARB) standards for 1994 and 1999. CARB standards for 1994 can be achieved through leaner fuel/air mixtures, and CARB standards for 1999 will probably require changes to engine design and exhaust gas treatment.[5] Initially, engine manufacturers changed basic operating parameters, such as the fuel/air ratio, ignition timing, and compression ratio. Leaner fuel/air ratio and changes in valve timing to reduce overlap and increase peak cylinder pressures help reduce CO emissions. Thermal oxidation of CO via air injection can

also effectively reduce CO emissions.[6] Incremental reductions in CO emissions from small, gasoline-powered engines by the previously mentioned methods may reduce the severity of CO exposures. However, these reductions will not eliminate CO exposures and poisonings.

Occupational Safety and Health Standards

The current Occupational Safety and Health Administration permissible exposure limit for CO is 50 ppm as an 8-hour time-weighted average.[7] The NIOSH recommended exposure limit for CO is a 35 ppm time-weighted average and a ceiling limit of 200 ppm. The immediately dangerous to life and health (IDLH) concentration for CO, as designated by NIOSH, is 1200 ppm. The IDLH is the concentration that could result in death or irreversible health effects.[8]

METHODOLOGY

The dilution ventilation equation was used to (1) determine whether it is safe to use a 5-hp, gasoline-powered engine indoors under various conditions; using the field data, various ventilation rates were placed in the model to predict CO concentrations and define "well-ventilated area" for the poisoning scenario; (2) estimate effective ventilation rates by observing contaminant decay and estimate CO generation rates by observing CO buildup in a room; and (3) compare field data with published emission rates.

A model was developed to determine the time required for a gasoline-powered, 5 hp, 4-cycle engine to reach the 200 ppm ceiling limit and 1200 ppm IDLH CO concentrations for room sizes of 1000 to 100,000 ft³ and general ventilation rates of 1 to 20 air changes per hour (ACH). Ventilation rates of 1 to 20 ACHs were chosen based on commonly recommended general ventilation rates in commercial and public buildings.[9] The CO generation rate used in the model was 670.7 g/hp-hr based on data from a 1991 Environmental Protection Agency study.[10] Ideal mixing of CO with the room air was assumed. The CO generation rate was converted to cubic feet per minute according to the following equation.

$$\frac{670.7 \text{ grams CO}}{\text{hp–hour}} * \frac{1 \text{ hour}}{60 \text{ minutes}} * \frac{5\text{hp}}{1} \frac{24.45 \text{ liters}}{\text{g-mole STP}} * \frac{\text{g-mole CO}}{28 \text{ grams}} * \frac{\text{ft}^3}{28.3 \text{ liters}} = \frac{1.72 \text{ ft}^3 \text{ CO}}{\text{minute}}$$

Modeling was performed by applying a simple material balance to CO in the room, which provided a basis for relating accumulation rate to generation and removal rate.[11] The situation can be described as follows.

Accumulation rate = generation rate − removal rate

$$V\frac{dC}{dt} = G - \frac{Q}{k}C \qquad (1)$$

where V = volume of the room (1000, 10,000, or 100,000 ft³)
    G = rate of contaminant generation (670.7 grams/hp-hr)
    Q = actual volumetric flow rate (1–20 ACH)
    k = mixing factor (ideal mixing assumed thus, k=1)
    C = concentration of the contaminant
    t = time (minutes)

The term on the left side of the material balance represents the rate of accumulation of the contaminant in the working environment, and the terms on the right represent the rate of contaminant generation minus the rate of contaminant removal. A mixing factor, k, varies from 1 to 10; a value of 1 represents ideal mixing, and 10 represents poor mixing.

Assuming k is constant in a well-mixed room with k=1, the actual ventilation rate, Q, can be replaced with the effective ventilation rate Q′. Using a constant generation rate, this equation can

be integrated with respect to concentration and time to yield the following.

$$\ln \frac{G - Q'C_2}{G - Q'C_1} = -\frac{Q'(t_2 - t_1)}{V} \qquad (2)$$

and this can be solved for C_2 assuming $C_1 = 0$, which results in

$$C_2 = G \frac{1 - e^{-Q'\frac{\Delta t}{V}}}{Q'} \times 10^6 \qquad (3)$$

where C_2 is in parts per million

    G is in cubic feet per minute

    Δt is in minutes

    V is in cubic feet, and

    Q' is in cubic feet per minute.

For any Δt, C_2 can be calculated because all other values are known. CO concentrations were calculated using a spreadsheet program (Microsoft Excel®, Version 5.0).

Actual field-generated data was compared with the model. In January 1996 two Colorado workers were poisoned as a result of operating a 5-hp walk-behind concrete saw during a remodeling project in a public bathroom at a municipal zoo. The machine was 3 years old and was used only two to three times per year. The workers operated the saw for about an hour and a half inside of what had previously been two bathrooms. The dividing wall between the rooms had been removed, resulting in a room volume of 2332 ft³. The workers were cutting a hole in the floor to allow access to pipes below. The two doors to the room were open, and the bathroom ventilation system was operating when these poisonings occurred.

The day after the poisonings, the work in this double bathroom was continued, but with two differences: A cooling fan was used in an attempt to remove CO from the room, and the saw was operated for shorter periods of time. Although operating times were not clearly defined, they were thought to last 15 to 30 minutes. The second-day operating conditions were recreated (with the bathroom fan on, the doors open, and the cooling fan on) to measure CO concentrations in the room. A Biosystems Toxilog Monitor (Biosystems, Inc., Middletown, Conn.) equipped with a CO sensor was used to measure CO. The CO monitor was mounted at breathing zone height in approximately the worker's operating position. No one occupied the room during the CO testing, and the saw was not under load.

To determine both the CO generation rate and ventilation rate during the field demonstration, the buildup and decay portions of the CO concentration profile must be analyzed separately. Each analysis results in an equation. From those equations, the two unknowns can be determined: the room ventilation rate and the CO generation rate. To determine the effective ventilation rate, the decay portion of the CO concentration curve was used. To determine the CO generation rate, the buildup portion of the CO concentration data was used in conjunction with the effective ventilation rate from the previous step.

RESULTS

Modeling Results

Effective Ventilation Rate

The rate of decrease of CO concentration in the room after the engine had been turned off can be characterized using the dif-

ferential material balance in the room. Note that the generation rate is zero and can be dropped from Equation 1, resulting in the following.[11]

$$VdC = -Q'Cdt \qquad (4)$$

where V is the volume of the room

    C is the CO concentration in the room

    Q' is the effective ventilation rate, and

    t is the time

Integration yields

$$\ln \frac{C_2}{C_1} = -\frac{Q'}{V}(t_2 - t_1) \qquad (5)$$

Although the size of the room is known (2332 ft³), the ventilation rate is not known because the combination of the bathroom ventilation system, the cooling fan, and the airflow through the two open doors was not characterized. The effective ventilation rate (Q') is the total ventilation rate provided by all the sources of ventilation divided by the mixing factor.

Solving for the only unknown, Q', yields

$$Q' = \frac{V \ln \frac{C_2}{C_1}}{t_2 - t_1} \qquad (6)$$

By inserting the values for V, C_1, C_2, t_1, and t_2, Q' can be calculated for each step of the CO concentration decay curve (see Table I.) The result is an average effective ventilation rate of 836 ft³/min with a standard deviation of 325 ft³/min. The ventilation variability is most likely due to opened doors being a major source of air movement, and CO concentrations being measured in a single location.

TABLE I. CO Field Data and Calculated Effective Ventilation and Generation Rates

Values Obtained in the Field Example		Calculated Values from Integrated Equations	
Time (min)	CO (ppm)	Q' (ft³/min)	G (g/hp-hr)
0	28		0.878
1	341		0.861
2	560		0.753
3	678		0.909
4	820		0.690
5	842	engine off	
6	775		
7	449	1273	
8	256	1310	
9	209	473	
10	158	652	
11	104	975	
12	75	762	
13	54	766	
14	44	478	
15	40	222	

CO Generation Rate

With the effective ventilation rate (Q') and several CO concentration measurements taken during the buildup stage, the CO generation rate can be calculated from the differential material balance in the room.[11]

$$\frac{dC}{G - Q'C} = \frac{dt}{V} \qquad (7)$$

where G is the generation rate for CO by the engine.

Integrating yields

$$\ln \frac{G - Q'C_2}{G - Q'C_1} = - \frac{Q'(t_2 - t_1)}{V} \qquad (8)$$

For this data (t_2-t_1) is always equal to one time unit and can be dropped from the equation. Solving for G produces

$$G = \frac{e^{\left(-\frac{Q'}{V}\right)} Q' C_1 - Q' C_2}{e^{\left(-\frac{Q'}{V}\right)} - 1} \qquad (9)$$
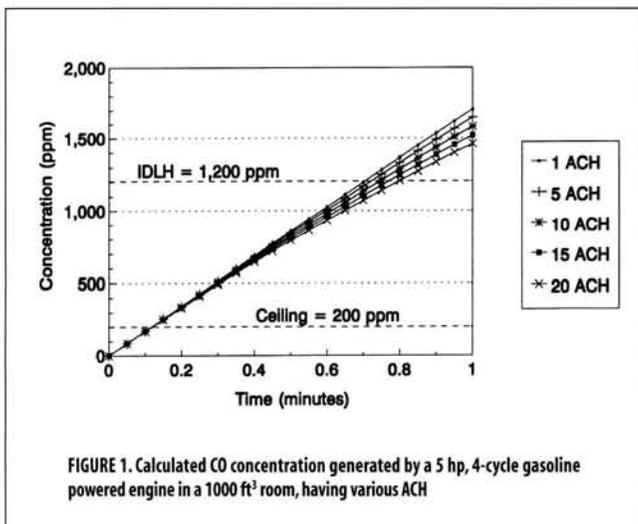
Inserting the values for V, C_1, C_2, and Q', G can be calculated for each increase in the CO concentration (see Table I.) The average CO generation rate based on these calculations is 0.818 ft³/min with a standard deviation of 0.085 ft³/min.

At standard temperature and pressure, the volume of CO obtained from the above calculation can be converted to a CO generation rate that is expressed in terms of grams per horsepower-hour.

$$\frac{0.818 \text{ ft}^3}{\text{Minute}} * \frac{28.3 \text{ liters}}{\text{ft}^3} * \frac{\text{g-mole STP}}{24.45 \text{ liters}} * \frac{28 \text{ grams}}{\text{g-mole CO}} * \frac{60 \text{ minutes}}{\text{hour}} * \frac{1}{5\text{hp}} = \frac{318 \text{ grams CO}}{\text{hp-hour}}$$
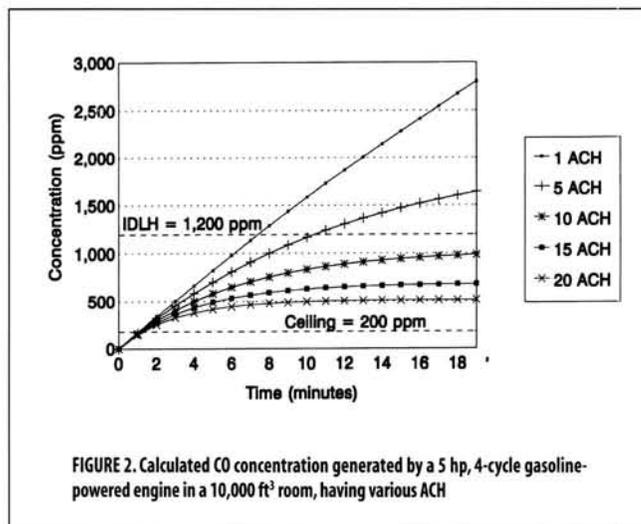
The generation rate (0.818 ft³/min) and room size (2332 ft³) from the poisoning simulation was then used in the model. The model was used to evaluate various airflow rates and determine the quantity of airflow that would have been required to maintain CO concentrations below the 200 ppm ceiling.

CO versus time (Equation 3) is plotted in Figures 1–3 for arbitrarily selected small (1000 ft³), medium (10,000 ft³), and large (100,000 ft³) areas for ventilation rates from 1–20 ACH and for conditions of perfect mixing (k=1). (Under actual conditions, if mixing were poor, hazardous concentrations near the engine could develop more quickly.) In the small room the ceiling concentration of 200 ppm was reached in approximately 0.1 minute, and the IDLH was reached in less than 1 minute at all airflow rates. In the medium room the IDLH was reached in approximately 7 minutes for 1 ACH and approximately 10 minutes for 5 ACH. In no case would it be possible to operate an engine for 8 hours without exceeding the NIOSH 35 ppm recommended exposure level for CO.

FIGURE 1. Calculated CO concentration generated by a 5 hp, 4-cycle gasoline powered engine in a 1000 ft³ room, having various ACH
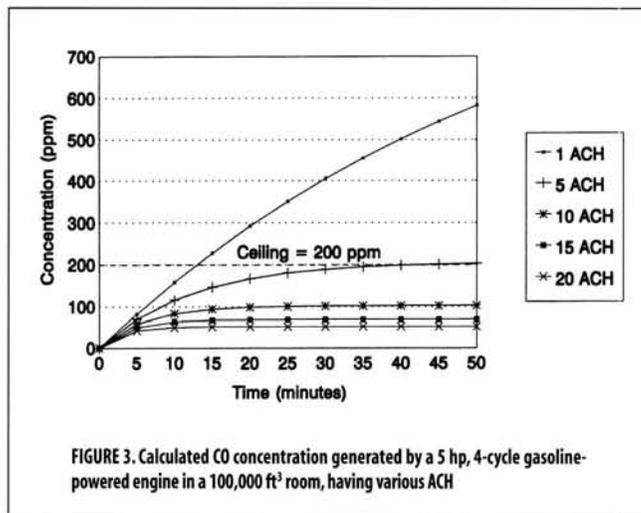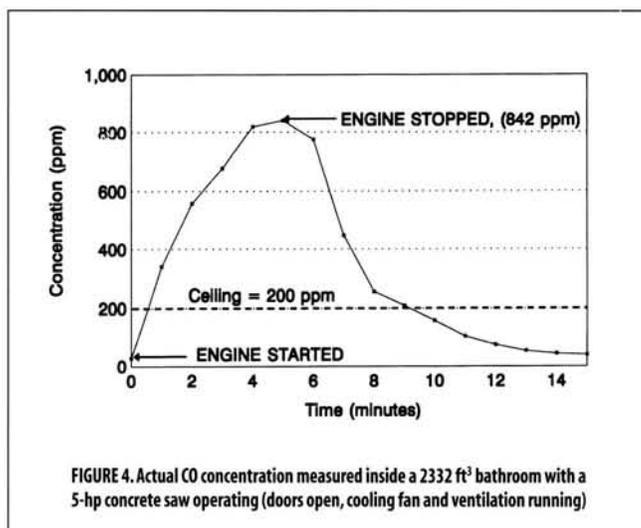
Field Data Analysis Results

CO concentration data from the poisoning simulation are shown in Table I and Figure 4, demonstrating that the NIOSH ceiling

FIGURE 2. Calculated CO concentration generated by a 5 hp, 4-cycle gasoline-powered engine in a 10,000 ft³ room, having various ACH

limit was exceeded within the first minute of operation. Within 4 minutes of operation the CO concentration within the room exceeded 800 ppm, and at 5 minutes the engine was turned off.

FIGURE 3. Calculated CO concentration generated by a 5 hp, 4-cycle gasoline-powered engine in a 100,000 ft³ room, having various ACH

By placing the room size and generation rate from the poisoning simulation into the model, it was possible to evaluate how various airflow rates would have affected the CO concentrations (Figure 5). The actual effective ventilation rate from the opened

FIGURE 4. Actual CO concentration measured inside a 2332 ft³ bathroom with a 5-hp concrete saw operating (doors open, cooling fan and ventilation running)

doors and fan was approximately 836 ft³/min (21.5 ACH). The model demonstrated that ventilation rates of 30, 60, and 90 ACHs were insufficient to control CO concentration below the 200 ppm ceiling concentration for even relatively short periods. Nearly 5000 ft³/min (120 ACH) would be required to prevent the CO concentration from exceeding the ceiling concentration.

FIGURE 5. Calculated CO concentration by inserting room size and generation rate into model and examining actual and higher ventilation rates. Note that 120 ACH are needed to keep the CO concentration below the ceiling of 200 ppm
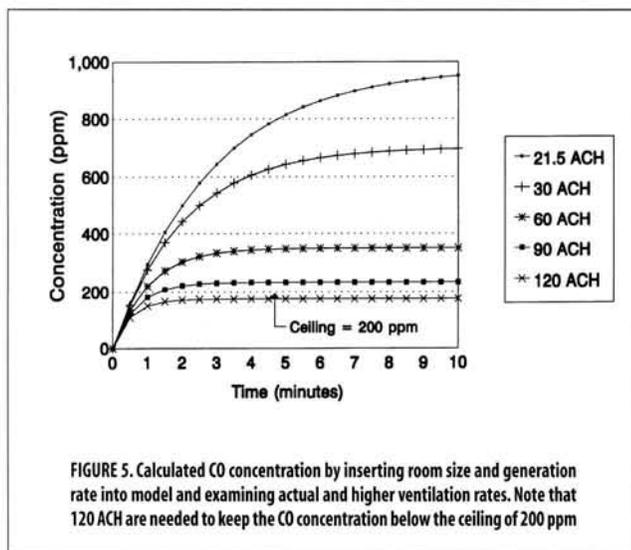
DISCUSSION

Both the modeling data and field generated data indicate that hazardous concentrations of CO can be generated by these engines in a matter of minutes. Clearly, as the room size and ventilation rates increase, the time required to reach hazardous concentrations also increases. However, based on each of the modeling scenarios, exposure to such conditions is not safe for any worker. Many workers do not understand how quickly hazardous concentrations can develop (even in large areas with significant airflow).

When the field data is compared with modeling data, the CO generation rate is approximately one half of the value used in the model. These engines can produce a wide range of generation rates that vary depending on many different factors, such as the engine loading and speed, air/fuel ratio, ignition timing, and compression ratio. For the field data, running the engine under no load may have been the major factor resulting in CO generation rates that were approximately 50% of the model. The generation rate for the model was based on Environmental Protection Agency data that included an operating engine under various loading scenarios. However, when dealing with life and death, worst case (full load conditions) is prudent. By applying the actual poisoning conditions to the model, it was clear that extremely high ventilation rates would have been required to reduce the hazard with dilution ventilation. Even at ventilation rates of 60 or 90 ACH, hazardous concentrations would develop within minutes.

CONCLUSIONS AND RECOMMENDATIONS

CO is a potent, lethal gas that can overcome exposed persons without warning. Many workers in buildings or semienclosed spaces have been poisoned by CO while using gasoline-powered tools, such as high pressure washers, concrete cutting saws, power trowels, floor buffers, welders, pumps, compressors, and generators. CO can rapidly accumulate, even in areas that appear to be well-ventilated, resulting in dangerous and fatal concentrations within minutes. Incremental reductions in CO emissions by modifying engine design or operating parameters may slow the generation rate. However, these measures will not eliminate CO exposure and poisonings. Likewise, CO is also produced from small utility engines operating on alternative fuels, such as liquified petroleum gas. If engines running on alternative fuels are not properly adjusted, hazardous CO concentrations can be produced.

Small, gasoline-powered engines should not be operated inside of buildings or in semienclosed spaces where CO can accumulate (even if some ventilation is provided). Workers need to be informed that opened windows or doors or an operating fan clearly does not provide sufficient ventilation. They should have a better understanding of the extent of this hazard and realize that tools powered by electric or compressed air may be an appropriate alternative.

Manufacturers of these tools could reduce their liability through a number of measures. Tools that generate CO and could be used in buildings or semienclosed spaces should have concise, conspicuous, and unambiguous warnings.[12] User manuals should provide information concerning the symptoms of CO overexposure: headache, nausea, weakness, dizziness, visual disturbances, changes in personality, or unconsciousness.[13] Manufacturers should also conduct research and begin to develop engineering control options to provide better protection for their customers.

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