February 1994

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ABSTRACT: Fumigation is the most effective method of rabbit *(Oryctolagus cuniculus)* control available in the United Kingdom. Use of current methods, involving formulations that generate hydrogen cyanide (HCN) or phosphine (PH_3) on exposure to moisture, is limited by weather conditions. A carbon monoxide producing cartridge has been developed which can be used independent of weather conditions. The cartridge is similar in size to the smaller carbon monoxide (CO) cartridge used in the United States, but produces up to 70% more CO. High concentrations of CO were measured at the entrances of an unoccupied artificial warren fumigated with CO-cartridges, but these declined quickly. There was relatively little movement of CO through the warren but in most parts concentrations of _>.l % were maintained for one hour or more. Wind speed and direction were shown to have significant effects on CO concentration and distribution.

Proc. 16th Vertebr. Pest Conf. (W.S. Halverson& A.C. Crabb, Eds.) Published at Univ. of Calif., Davis. 1994.

INTRODUCTION

The most effective method available for reducing rabbit *(Oryctolagus cuniculus)* numbers in Great Britain is fumigation of rabbit warrens. Formulations which release hydrogen cyanide (HCN) or phosphine (PH_3) in response to moisture are currently approved for such use, but all such formulations are potentially hazardous and their use is limited by weather conditions (Roe and McKillop 1982). PH_3-generating formulations are more convenient to use (Ross 1986) for rabbit control than those releasing HCN.

In mammals, carbon monoxide (CO) replaces oxygen in the hemoglobin of arterial blood leading eventually to a depletion of oxygen to the brain, resulting in collapse, unconsciousness, and death. A recent review of the toxicology of CO to mammals (Ross unpublished) suggests that carbon monoxide could be a humane fumigant for use in the control of wild rabbits, provided that animals are exposed to concentrations of 1% or greater.

Carbon monoxide has been used successfully for vertebrate pest control in a number of countries (Savarie et al. 1980, Deng and Zhao 1986, Pelz and Gemmeke 1988) against a variety of species including many species of burrowing rodents, coyotes *(Canis latrans),* rats *(Rattus* sp), and water voles *(Arvicola terrestris)*. CO used for pest control has been produced by charcoal-burning in a stove mounted on a vehicle, from motor exhaust (Oliver and Blackshaw 1979), or by combustion of a cartridge containing a source of carbon (charcoal or sawdust) and a source of oxygen (potassium or sodium nitrate):

$$4C + 2NaNO_3 \text{ -» } 3CO + Na_2CO_3 + N_2$$

The last method was used by Savarie et al. (1980), who developed two different cartridges for the control of coyotes and small burrowing animals. These cartridges are available commercially in the United States (USA), but are unsuitable for use against rabbits in Great Britain (UK); the larger (240 g) cartridge is too large for rabbit burrows and the other (65 g) cartridge, although of suitable size, contains a number of ingredients, apart from sodium nitrate and charcoal, which generate a number of other toxic and irritant gases.

The use of a CO cartridge as a fumigant has several potential advantages over the currently available fumigants. It would be unaffected by weather conditions, the ingredients of the cartridge are inert until ignited and the CO is generated within the warren. The aim of the present work was to develop a cartridge producing only CO and carbon dioxide (CO_2) at least as efficiently as the larger USA cartridge and to investigate the ability of the cartridges to produce concentrations of _>_1 % of CO in an artificial rabbit warren.

Weinhouse (1948) used an alternative method of CO production by igniting a mixture of magnesite ($MgCO_3$) and zinc dust, according to the equation:

$$MgCO_3 + Zn \text{ -» } MgO + ZnO + CO$$

Therefore, $MgCO_3$ and zinc dust, or zinc oxide, were added to sodium nitrate and charcoal in attempts to increase CO production.

METHODS

Laboratory Investigations

Preliminary tests. In order to establish the most efficient mixture for producing CO, preliminary tests were carried out to determine the effects of varying the proportions of sodium nitrate and charcoal. Twenty-five gram amounts of mixtures containing different proportions were ignited in a 75 1 glass tank at ambient temperature and pressure. CO concentrations were measured using gas analyzer tubes (Gastec, middle and extra high ranges).

Cartridges. Since the packaging, $NaNO_3$ and charcoal available in the UK were not identical to those in the USA cartridges, an investigation was carried out into the effects on CO production of varying the packaging and ingredients. Two types of cartridges, each containing approximately 65 g of mixture were investigated and their CO production, mixture, and packing compared. The USA cartridge (65 gm), as used in these tests, was produced from the packaging and mixture (65% $NaNO_2$ and 35 % charcoal) used in the 240 g cartridge (Pocatello Supply Depot, Idaho). The packaging was made by cutting sections from the 240 g cartridge, which consisted of strips of cardboard 1.5 mm thick formed into a spiral

tube and cut into 71 mm lengths x 40.5 mm external diameter. Both ends were sealed with cardboard closures, one of which had provision for perforations for ten gas outlets plus one for the fuse.

The Central Science Laboratory (CSL) cartridge was made from CSL mixture and CSL packing. CSL mixture was a mixture of prilled sodium nitrate (Chilean) from Ellis Everard London, and charcoal (granular activated, particle size 0.85 to 1.70 mm) from Merck Chemicals, Poole. The CSL packing was made first from paper and then from cardboard tubes (Sonoco Ltd., Huddersfield) almost identical to the USA cartridge with cardboard closures (BDH, Poole) similarly perforated with gas outlets and a fuse.

Each fuse was made into a tuning fork configuration from two 18 cm lengths of slow plastic igniter cord (ICI Nobel's Explosives) and inserted into the cartridge as it was filled.

Test procedure. The experiments were carried out in a 260 1 stainless steel chamber capable of holding a vacuum, fitted with five small ports, and two inlet/outlet valves. A vacuum pump was used to purge gas from the chamber to the atmosphere at the end of each test.

The fuse of each cartridge was ignited electrically within the chamber at half normal atmospheric pressure. The maximum temperature and pressure were recorded together with the interval from ignition to gas sampling. The chamber and its contents were allowed to cool to below 40° C and reach normal atmospheric pressure before measure the CO concentration produced by each cartridge using Gastec gas analyzer tubes inserted through one of the chamber's ports and fitted directly to a hand sampling pump.

The accuracy of the Gastec gas analyzer tubes for CO was compared against gas chromatography (GC Hewlett Packard 5880) readings using a thermal conductivity detector (TCD), with an approximate accuracy of _+10%, and against known concentrations of CO in the chamber. To do this the stainless steel chamber was filled with different known concentrations of CO from a gas cylinder (Air Products 99.5 % CO) and simultaneous measurements made by gas analyzer tubes and by gas chromatography.

Alternative formulations. Zinc powder and either lithium carbonate (Merck Chemicals) or magnesium carbonate (Magnesite - granular, Pharmacos Ltd., Southend, Essex) were added to the CSL cartridge in an attempt to increase CO production (Weinhouse 1948).

Effect of gradient. The effect of gradient on the flow of CO gas was investigated by igniting a cartridge in one end of a 5.5 m length of asbestos pipe (sealed with a polythene bag at the other end) and measuring the CO concentrations at the other end, when the end 2.9 m of the pipe, distant from the cartridge, was sloping at approximately 22° either upwards or downwards.

Field Investigations

An artificial rabbit warren (approximately volume 300 1) was constructed within a mound made from a mixture of approximately equal parts of top soil and sand, standing approximately 1 m above general ground level. The warren (Figure 1) consisted of approximately 18.5 m of tunnels (approximate diameter 15 cm) made from plastic netting (Tensar SS2, 28 mm x 40 mm, Netlon Ltd.) with six entrances (four "normal"—1, 5, 9 and 12, and two "pop-holes"--13 and 14) and five blind ends (Figure 1). Fourteen gas sampling points were built into the warren, enabling the atmosphere to be sampled at strategic points. Temperature probes (copper/constantan thermocouples connected to a Yokogawa HR 2300 hybrid recorder) were inserted into nine sample points (2, 3, 4, 6, 7, 8, 10, 11, and 12).

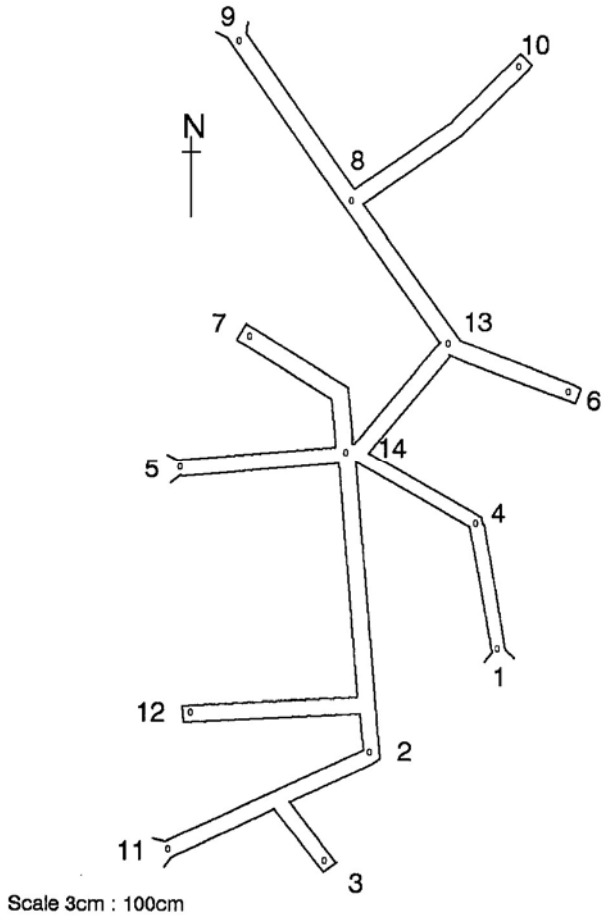

Figure 1. Plan of artificial warren showing location of 14 gas sampling points.

Wind speed and direction were recorded manually during each test using a hand anemometer mounted on a post, slightly higher than the top of the warren.

For each test, two cartridges were ignited in quick succession within each of the six entrances, which were then sealed with sandbags.

An electric motor and a gasoline engine were used in later tests to try to increase the levels of carbon monoxide within those parts of the warren most remote from the entrances.

Management of CO Concentration

Nylon 6 tubing (3 mm diameter) was inserted into gas sampling points and CO concentration measured using

either gas analyzer tubes (Gastec middle and extra high ranges) with Gastec pumps or gas chromatography equipment housed in a mobile laboratory.

A Hewlett Packard 5880 gas chromatograph was fitted with a thermal conductivity detector. To prevent interference from CO_2 and water vapor, small guard tubes packed with carbosorb (AS) were fitted in the gas sampling lines.

Initially two series of tests were carried out, each with four replicates followed by further tests each with two replicates.

RESULTS

Laboratory Investigations

In the preliminary tests, the mean CO concentrations from mixtures of $NaNO_3$ and charcoal are as shown in Table 1. A mixture of 65% $NaNO_3$ + 35% charcoal (as used by Savarie et al. 1980) produced the most CO and was used as the CSL mixture in all further tests.

Table 1. Preliminary tests of CO production from different proportions of sodium nitrate and charcoal.

Type of Mixture		Carbon Monoxide	
$NaNO_3$ %	Charcoal %	%	S.D.
60	40	0.00	*
65	35	0.94	0.261
70	30	0.86	0.114

* Cartridges failed to ignite.

Tests of CO production in the stainless steel chamber showed that there was no significant difference in the amounts of CO evolved between the USA cartridge (0.97% CO) and the CSL cartridge (0.78% CO) (Mann-Whitney test, U = 29, n.s.) (Table 2). Tests also showed that there was no significant difference in CO concentrations produced using the CSL mixture in the CSL packing (cardboard) or the USA packing (Mann-Whitney test, U = 78.0, n.s.) (Table 2).

Tests to investigate the effect on CO production of adding magnesium carbonate and zinc to the CSL cartridge showed that temperatures of 500° to 800°C, in excess of the melting point of $MgCO_3$ (350°C), were attained. Nevertheless, the mixture of Zn and $MgCO_3$ remained unaltered, and a maximum of 1.8 1 (0.7%) of CO was generated. No further tests were carried out on mixtures of carbonates (magnesium or lithium) and zinc in combination with sodium nitrate and charcoal.

Subsequent development of the cartridge succeeded in increasing the production of CO to 1.9% in the test chamber. These tests (Table 3) to investigate the effect on CO production of adding ZnO to the CSL cartridge show that significantly higher concentrations of CO resulted from the addition of 20% ZnO to the CSL mixture ($F_{3il5} = 0.006$; $P < 0.001$).

Table 2. The relative amounts of carbon monoxide produced in a chamber by varying the mixture and the packaging in which it is burnt.

No. of cart-ridges	Type of mixture	Type of packaging	Carbon monoxide %
11	CSL	CSL	0.78 SD 0.178
18	CSL	USA	0.82 SD 0.337
8	USA	USA	0.97 SD 0.484

Table 3. The effect of adding zinc oxide to the CSL mixture of sodium nitrate and charcoal on CO production.

ZnO %	n	Carbon monoxide %	
0	6	1.1	SD 0.318
10	3	1.0	SD 0.329
15	3	1.2	SD 0.329
20	4	1.9	SD 0.320

Effect of gradient. Tests to investigate the effect of gradient on CO gas movement showed that the mean CO concentration was 2.2% SD = 0.821 close to the cartridge in the entrance and 1.0% SD = 0.998 and 0.2% SD = 0.141 at the end of the downward and upward gradient, respectively. A two-tailed Mann-Whitney test showed that the amount of CO at the end of the pipe was significantly less if the slope was upward (U = 1.5; P < 0.0133).

Field Investigations

The type of cartridge that produced the greatest amount of CO in earlier tests was used—the improved CSL cartridge containing 65 g of a mixture of sodium nitrate, charcoal, and zinc oxide.

The accuracy of the Gastec gas analyzer tubes (claimed to be accurate to .+25%) was checked using simultaneous measurements taken by analyzer tube and by gas chromatography. The mathematical relationship

$$gc = 0.99096 \times gas^{11680}$$

was used throughout this study to convert analyzer tube (gas) to gas chromatograph (gc) measurements (Figure 2).

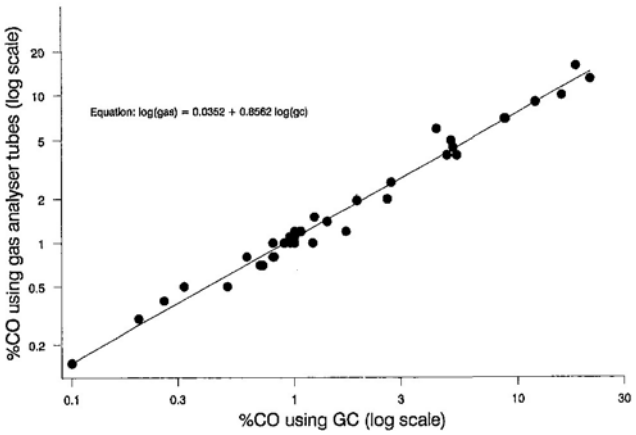

Figure 2. The relationship between carbon monoxide concentrations obtained from gas analyzer tubes and by gas chromatography.

Maximum CO concentrations at entrances were initially high (up to 33.5%), but decreased quickly over the first 20 to 30 minutes. Subsequently, wind influenced the variations in CO concentration; the greater the wind speed, the more rapid the decrease in percent CO. In relatively strong wind (15 to 25 km/h) the CO concentration at entrance 1 fell to just over 1% in 100 minutes; whereas in the absence of any wind, the CO concentration at entrance 1 remained over 4 % for at least 180 minutes.

Wind direction and speed also affected the distribution of CO within the warren. CO was detected in the blind end furthest from an entrance (sample point 10) only during the two tests with highest wind speeds when that blind end was the part of the warren farthest downwind. Also, in the same two tests CO concentration decreased at the two windward entrances (5 and 11) more quickly than in tests with light winds.

In the main tunnels, the CO concentrations appear to be relatively high (generally remaining above 1 % for one hour or more (Table 4). The CO concentrations at the blind ends (sample points 3, 12, 7, 6, and 10) were variable; sometimes, relatively high (e.g., remaining at or above 3 % for at least 2 h 40 mins at sample point 3) and sometimes low (e.g., CO concentration at sample point 12 was generally zero but, on one occasion, up to 0.7% after one hour).

The results illustrated that diffusion of CO along the tunnels was very poor. There was great disparity between the CO concentrations at sample points 13 and 6, which were 1.3 m apart and between sample points 11 and 2, which were 2 m apart. The use of gasoline and electric air pumps to increase the dispersal of carbon monoxide (i.e., from high to low concentrations of CO) within the warren was unsuccessful.

Significant increases in air temperature in the warren were confined to the entrances, where a maximum temperature of 38°C was recorded for only one minute immediately after cartridges were lit. In the main tunnels temperatures never rose more than *6°C* above pre-test levels. Thus, it is unlikely that rabbits would be exposed to temperatures that would cause adverse effects.

DISCUSSION Laboratory Investigations

Preliminary investigations in the laboratory showed that the amount of CO evolved could not be significantly increased by varying the proportions of sodium nitrate and charcoal. It was not considered practical, at this stage, to remove the many variables of mixture, packing, and prill size but these variables were reduced as much as possible.

In early tests, white paper was used to contain the CSL mixture to reduce production of smoke. It was found that the unburnt mixture was spilled as the paper burned and little CO was produced (0.3% and 0.2%). When cardboard was used (Table 2), much higher concentrations of CO were produced. Thus, for effective CO production it appears that the mixture must be contained in a cardboard cartridge.

In theory, a 65 g cartridge of 65 % sodium nitrate and 35% charcoal (CSL mixture only) would produce 31.85 1 of CO at STP, based on the equation for CO production being:

$4C + 2NaNO_3$ -* $3CO + NajCOj + N_2$ The maximum CO concentration produced in the chamber in this study, with a cartridge containing $NaNO_3$ and charcoal only, was 1.1%—equivalent to 2.86 1 of CO at half atmospheric pressure. Thus, CO production appears to be only 9% of that predicted theoretically. It is difficult to explain this finding, although production of CO_2 would, of course, reduce the quantity of CO produced; a small proportion of the charcoal is in powder form and is blown out of the cartridge without being burnt, and some of the contents fail to react because of spillage out of the cartidge, but it is unlikely that these factors could fully explain the poor production of CO. Although CO production was improved to 1.9% or 4.9 / per cartridge by addition of zinc oxide, it was still only 15% of the theoretical production. Zinc oxide is thought to react as in the equations: ZnO + C -♦ CO + Zn ZN + CO_2 -» CO + ZnO to increase the amount of CO produced. The presence of zinc oxide was observed to reduce the spillage of material from the cartridge, and this may also help to explain the higher amount of CO produced.

Twenty percent ZnO gave the highest concentration of CO of any of the proportions tested, but neither the theoretical proportion of ZnO for optimum CO production nor the theoretical amount of CO produced by adding 20% ZnO to the CSL cartridge were calculated. Valid quantitative calculations were impossible as the exact nature of the chemical reactions were unknown.

Further modifications to maximize the CO production of a fumigant cartridge are unlikely to be beneficial at this stage because the CSL mixture + 20% ZnO should produce lethal concentrations of CO gas within a rabbit burrow.

Carbon monoxide is slightly lighter than air (specific gravity 0.96716) but, in practice, this did not appear to

Table 4. Mean (and ranges) of carbon monoxide concentrations within artificial warren treated with two improved CSL cartridges per entrance (10 replicates).

	Mean time from ignition of cartridges (with ranges of times)		
Position	12.1 Mins (1 to 24.0)	44.2 Mins (31.0 to 60)	74.5 Mins (61 to 85)
Entrance (1,5,9,11,13)	12.3% (0.0 to 35.5)	5.0% (0.3 to 18.0)	2.9% (0.1 to 11.0)
Main Tunnels (2,4,8)	4.3% (0.1 to 16.0)	2.4% (0.0 to 10.0)	1.6% (0.1 to 7.0)
Blind Ends (3,6,7,10,12)	1.6% (0.0 to 10.5)	1.2% (0.0 to 6.0)	1.0% (0.0 to 5.8)

influence the dispersal of the CO fumigant gas as shown by the relatively low CO concentration at the end of an upward sloping pipe. Temperatures of over 1000°C were recorded within a burning cartridge and the effects of this heat, and the force with which gas and smoke was emitted, on air movements within the burrow would be expected to be considerable. However, the polythene bag at the end of the pipe inflated only slowly, even when below the level of the cartridge.

Field Investigations

The results obtained indicate that the improved CSL cartridge has the potential of delivering adequate concentrations of CO to most of the artificial warren. Further development will concentrate on improving the distribution of CO to ensure that the method is effective.

The CO concentrations produced within the warren and the effects of dispersal through the warren indicated that a large proportion of the CO produced was lost by diffusion through the soil which was greater than diffusion along the airspace within the tunnel. Carbon monoxide is almost insoluble in water and thus dissolution in soil moisture cannot explain the loss of CO from the fumigated warren, in contrast to HCN with which dissolution in soil moisture is a major factor in loss of HCN in the warren.

The results clearly showed that wind has significant effects on the persistence and distribution of CO in the artificial warren. The artificial warren was built above the existing soil surface and this has made the warren more exposed to wind than most natural warrens. However, the effects of wind should not be disregarded. Further tests in a range of wind conditions will enable more precise assessment to be made of the effects of wind, including, possibly, wind conditions that render the method ineffective.

ACKNOWLEDGMENTS

This study was funded by the Countryside Division of the Ministry of Agriculture, Fisheries and Food. The assistance given by D. J. Haskell, S. D. Langton, A. Nadian, D. Poole, and T. Wontner-Smith is gratefully acknowledged, as is the support and helpful criticism of the manuscript given by Dr. J. Ross. I am grateful to the Pocatello Supply Depot, Idaho, for the gift of a small number of both large and small gas cartridges.

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