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Review

Lethal Carbon Monoxide Poisoning in Wood Pellet Storerooms—Two Cases and a Review of the Literature

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The installation of wood pellet heating as a cost-effective and climatically neutral source of energy for private households has increased steadily in recent years. We report two deaths that occurred within the space of about a year in wood pellet storerooms of private households in German-speaking countries and were investigated by forensic medical teams. This is the first report of fatalities in this special context as is shown in the literature review. Both victims died of carbon monoxide (CO) poisoning; one of the victims was a woman who was 4 months pregnant. Measurements at the scene detected life-threatening CO concentrations (7500 ppm, >500 ppm), which were not significantly reduced after ventilation of the storerooms as required by regulations. We carried out a series of experiments in order to confirm CO production by wood pellets. Thirty kilograms of freshly produced pellets from two different manufacturers were stored for 16 days in airtight containers at 26°C with different relative humidities. CO concentrations between 3100 and 4700 ppm were measured in all containers. There were no notable differences between the wood pellet products or storage at different humidities. Emission of CO from wood pellets has already been described, but fatal accidents have previously been reported only in association with pellet transport on cargo ships or storage in silos. It is therefore a new finding that fatal accidents may also occur in the wood pellet storerooms of private households. We show that significant CO concentrations can build up even when these rooms are ventilated in accordance with the regulations and that such levels may cause the death of healthy persons, as described in the following. As the safety recommendations from the wood pellet industry are inadequate, we consider that further fatal accidents are likely to occur and recommend urgent revision of the safety regulations.

Keywords: CO; poisoning; safety regulations; storerooms; wood pellets

INTRODUCTION

Wood pellet combustion produces heat by burning wood pellets. As it is considered to be particularly cost-effective and climatically neutral, wood pellet heating has increased substantially in recent years. According to the German Wood Fuel and Pellet Association (DEPV), the number of wood pellet heating systems in Germany increased from 3000 installations in the year 2000 to about 140 000 in 2010 (DEPV, 2011). Wood pellets are made from natural, compressed waste wood (sawdust, wood chips, shavings or off-cuts). In accordance with the European standard EN 14961-2 and the German versions EN-Plus A1 and EN-Plus A2, the pellets measure 31.5–40 mm in length and have a diameter of

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6–8 mm. They contain less than 10% water and must be produced from at least 98% pure wood, with a maximum of 2% binding additives such as starch. The calorific value of a kilogram of pellets is equivalent to 5 kWh and therefore the same as half a litre of heating oil (DEPV, 2011; HS, 2011).

Wood pellet heating can be used to supply energy to detached houses and to large residential developments. A major component of these heating systems is the pellet storeroom, which is usually a dry, airtight room from which the pellets are fed via a conveyor into the furnace located in an adjacent room. The thermal energy obtained is distributed throughout the building from a heat reservoir (Figs. 1 and 2). The wood pellets are blown into the storeroom via a pump hose through one or more filling ports. Every storeroom has a level gauge indicating the quantity of pellets in the storeroom. If possible, no one should enter the storeroom unless it is absolutely necessary for installation or maintenance. In this event, for storerooms with a capacity of up to 10 tons of pellets, the DEPV recommends that the heating should be switched off 1 h before entering the room. The storeroom should be adequately ventilated for 15 min prior to entry, by opening the main access door. In addition, the provision of special vented ceilings above the injection and suction connectors allows the exchange of air in the storeroom. A specially designed warning sign should be affixed at the entry to the pellet storeroom (Fig. 2) (DEPV, 2011; HS, 2011) To date, deaths from CO poisoning have only been described in association with the transport or storage of large quantities of wood pellets (Svedberg, 2008; Melin, 2010; Pa and Bi, 2010). Within the space of about a year, two deaths in wood pellet storerooms of private households occurred in German-speaking countries. In this paper we report these two cases on the basis of previous publications and describe our experiments to demonstrate the emission of CO from wood pellets.

CASES INVESTIGATED AND METHODS

Cases investigated

Case 1 At the end of January 2010, a 43-year-old engineer died in a small town in Germany after he opened a pellet bunker door, while a second worker who was standing right behind him was also affected but still able to call the emergency services. The pellet bunker had a storage capacity of approximately 155 tons of pellets, supplying about 700 households with heat. The two workers had to enter the storeroom because of problems with the filling level gauge for the wood pellets. Forensic investigation of the body was ordered to clarify the cause of death.

Case 2 The second case occurred at the beginning of February 2011 in a medium-sized Swiss town, where a 28-year-old woman who was 4 months pregnant was found dead in an 82-m^3 pellet storeroom.

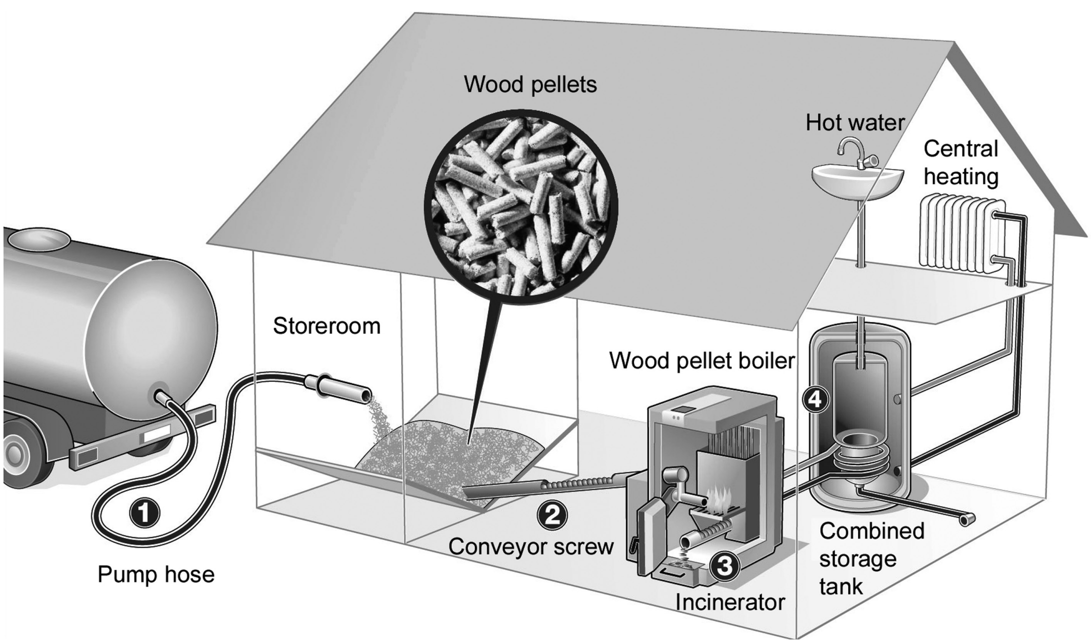

Fig. 1. Wood pellet heating system (source http://www.unendlich-viel-energie.de, modified from Gauthier and Bartsch)

Fig. 2. Warning sign and Safety instructions from the DEPV (http://www.propellets.ch/fileadmin/user_resources/publications/902_Hinweisschild_Pelletlager-gross_d.pdf translated)

The wood pellet heating system supplied 60 households. In this case, there was a problem with the wood pellet conveyor, so the caretaker's wife went to inspect the problem on his behalf. As the woman's body was found almost completely wedged beneath the circular cover above the opening of the screw conveyor, it was initially assumed that the accident was primarily of a mechanical nature. However, when external examination of the body revealed bright red lividity of the skin and fingernail beds, giving rise to the suspicion of CO poisoning, the body was sent for a full postmortem examination.

Measurement methods

The storeroom where the body of the young woman was found contained a quantity of pellets equivalent to about one-third of its total capacity. Measurements made at the scene a few days after her death showed a room temperature of 26°C, relative humidity of 48%, and a CO concentration of 7500 ppm. The CO concentration was still 2000 ppm after ventilating the room, according to the regulations, for 2 h. The key question of whether the CO came from the wood pellets in the storeroom or from combustion in the furnace was resolved by the fact that no defect was found in the installation and by our own experiments. Ten wide-necked 60-l containers made of hard polyethylene were each filled with 30 kg of fresh wood pellets and closed with an airtight lid. The pellets came from two different manufacturers; five containers were filled with pellets from manufacturer A and five from manufacturer B. The pellets differed in their composition with one type being pure spruce and the other spruce with a high proportion of bark. Both types were manufactured in compliance with the DINplus standard (equivalent to EN-PlusA1) and packed immediately after the cooling step following production. One day after being filled with pellets, each of the five containers from the two manufacturers was sprayed with a fine jet of water from a commercial garden hose to provide moisture at different concentrations: 0, 1, 2, 3, and 4% of the net weight of the pellets. The containers were then placed in a room with a constant ambient temperature of 26°C. After 16 days, a hole was bored into the container and a probe inserted to measure the CO and O_2 content using the Ecom-J2KN emission analyser. At the same time, the humidity in the headspace was measured using a Testoterm probe. We did not measure the CO_2 content. The holes were then resealed to keep the containers airtight. Humidity was again measured in the same way 3 weeks later, i.e. 37 days after the pellets had been packed.

Table 1. Measurements of CO emission by wood pellets from different manufacturers.

	Manufacturer A					Manufacturer B				
Water added (% of pellet weight)	0	1	2	3	4	0	1	2	3	4
Temperature (°C)	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
Relative humidity (%)	27	33	46	48	59	39	47	54	60	58
CO content (ppm)	3610	4727	4313	2294	3059	4445	4780	3706	4685	3095
O_2 content (%)	9.3	6.8	8.1	10.3	11.5	7.0	7.1	10.1	7.4	10.7

RESULTS

Chemico-toxicological investigation of the peripheral blood carried out as part of the postmortem examination of the first victim showed a lethal CO concentration of 60% COHb. The second worker, who was found in front of the bunker door, was treated in a university hospital, where a CO concentration of 16% COHb was measured in his blood. Several measurements made at the scene of the accident, immediately after the two workers had been found, detected air with CO concentrations of more than 500 ppm. One year before, values of 1000 ppm CO had been measured during a test procedure. Measurements made during research in connection with the accident demonstrated a maximum CO concentration of 53 700 ppm in the airtight storeroom; the CO concentration increased each time after the filling procedure. Combustion or a defect in the heating system was ruled out as the source of the CO. A warning sign was attached to the outside of the bunker hatch, warning of danger to life on entering the bunker (Fig. 2). Postmortem examination and chemico-toxicological analysis of blood taken from the heart of the second body confirmed the suspicion of lethal CO poisoning; the CO concentration was 75% COHb. Apart from the characteristic findings of CO poisoning described previously, there were several signs of blunt trauma such as lacerated contusions, abrasions, bruising, and fractures, all of which were considered to have occurred around the time of death or immediately afterwards, as there was no indication that they had occurred while the patient was still alive. Postmortem examination revealed a male fetus showing normal organ development compatible with 14 weeks' gestation. Toxicological investigation of the fetal lung tissue showed a CO concentration of 2% COHb, whereas the concentration in the fetal placenta was 4% COHb. A warning sign had been hung on the door to the pellet storeroom (Fig. 2), but it could not be seen once the door was open. This resulted in people entering the room after the victim had been found and unwittingly exposing themselves to the risk of CO intoxication. One member of the recovery team complained of headache and dizziness, typical symptoms of incipient CO poisoning, the following day.

Results of the measurements

Table 1 shows that CO concentrations between 3100 and 4700 ppm were found in all the containers tested. The humidity ranged from 27 to 60%. The oxygen levels were low, between 6.8% and 11.5%. Changes in the relative humidity had no significant relationship to CO production. Likewise, there was no difference in CO production between the pellets from the two manufacturers.

DISCUSSION

This work shows that there is a considerable risk to life and limb from airtight wood pellet storerooms in private households—a danger which, as far as we know, has not been described previously in the scientific literature. There are several reports in the literature of life-threatening concentrations of CO being produced by wood pellets and other wood products (Table 2).

In November 2006, there were one fatal CO poisoning and one of injury on a cargo ship in port in Helsingborg. The injured person survived with severe CO intoxication of about 44% COHb. This incident occurred when some workers used a non-ventilated stairway next to the cargo hold (SMSI, 2007; Svedberg *et al.*, 2008; Pa and Bi, 2010). The first documented accident of a similar nature occurred in 2002 in Rotterdam, where one person entering the hold of a ship transporting wood pellets died of CO poisoning and three others were also affected; this accident was not investigated further (SMSI, 2007; Melin, 2010). Since 2002, there have been reports of altogether 14 deaths and several non-fatal incidents. Nine of these fatal accidents occurred in connection with wood pellets, where five victims died after entering wood pellet storage rooms or silos (Table 2). Besides the two cases, which are represented in this

Table 2. Chronology of reported lethal CO poisoning due to wood pellets.

Date	Country /town	Location	No. of deaths	% COHb	No. of injured	% COHb	Main statements	Reference
05/2002	Netherlands/ Rotterdam	Cargo hold, Wood pellets	1	n	3	n	Lethal levels of CO may be rapidly produced in confined spaces Recommendations for safety instructions Recommendations for wood pellet industry	Svedberg *et al*. (2008) SMSI (2007) Melin (2010)
n/2003	USA	Cargo hold, Timber	1	n	n	n	n	SMSI (2007)
08/2005	Sweden/ Gruvön	Cargo hold, Pulpwood	1	n	n	n	Necessity of improvement of safety instructions Importance of training of crew members Requirement of technical methods for prevention of further accidents	Svedberg *et al*. (2009) SMSI (2007)
11/2006	Sweden/ Helsingborg	Cargo hold, Woodpellets	1	n	1	43, 8	See above	Svedberg *et al*. (2008) SMSI (2007)
							CO emission increases with storage temperature initially and decreases after reaching a peak A ventilation rate to reach a defined concentration of CO in the stairways of cargo holds is suggested	Pa and Bi (2010)
12/2006	Sweden/Skel-leftehamn	Cargo hold, Wood chips	1	n	n	n	See above	Svedberg *et al*. (2009) SMSI (2007) Svedberg and Knutsson (2011)
05/2007	Sweden/ Timra	Cargo hold, n	2	n	n	n	See above	Svedberg *et al*. (2009) Svedberg and Knutsson (2011)
n/2007	Finland/n	Pellets silo	1	n	n	n	n	Svedberg and Knutsson (2011)
n/2008	Finland/n	Pellets silo	1	n	n	n	n	Svedberg and Knutsson (2011)
n/2009	Denmark/ Bornholm	Cargo hold, Wood pellets	2	n	n	n	n	Svedberg and Knutsson (2011)
01/2010	Germany/ Remscheid	Private household, Wood pellets	1	60	None	—	Risk of CO poisoning in wood pellet storerooms of private house-holds is underestimated Necessity of improvement of safety instructions Importance of training of people who may have to enter wood pellet storerooms	this study
11/2010	Ireland/ Dublin	Private household, Wood pellets	1	n	2	n	n	Svedberg and Knutsson (2011)
02/2011	Switzerland/ Luzern	Private household, Wood pellets	1	75	None	—	See above	this study

n = no further information available.

study, there was a similar case that occurred in Ireland in November 2010, where one man died after entering a 7-ton pellet storage room. The deaths of two workers in two wood pellet silos were reported from Finland in 2008. Altogether nine of the fatal accidents had happened on cargo ships after sea transportation, four of which happened in connection with wood pellets. Three of those nine were due to other wooden products like timber or pulpwood and two cases happened in Timra, Sweden, where no further information was available (Table 2). The people involved had also used non-ventilated stairways to cargo holds containing wood pellets, wood chips or logs (Svedberg *et al.*, 2009; Pa and Bi, 2010). The extent to which these reported deaths could actually be attributed to lethal CO poisoning cannot be deduced from the literature; other causes such as significant oxygen depletion may also have been responsible. The fact is, however, that even though gas poisoning due to wood pellets has been reported in association with cargo ships and silos, deaths in private buildings have not previously been described in scientific publications.

In reporting these two cases and our research, we consider it important to call attention to the danger of lethal CO poisoning in the wood pellet storerooms of residential buildings. In both cases presented here, authorized persons entered the storeroom because of technical problems. In the first case, it was an engineer who had been informed of a problem with the pellet level gauge; in the second, the caretaker's wife was looking into a reported problem with the pellet conveyor system on his behalf. This case was particularly tragic because the victim was 4 months pregnant. The very low concentrations of CO found in the fetus (2% COHb in the lungs and 4% COHb in the fetal placenta) may be explained by a functioning placental barrier inhibiting CO diffusion across the placenta from the maternal blood. More detailed studies on fetomaternal transfer in pregnant sheep have shown that this situation does occur (Bissonnette *et al*., 1977). Furthermore, the higher affinity of fetal haemoglobin to CO is well known, but studies in pregnant women have shown that the uptake of CO and the peak of concentration in the fetal blood lag several hours behind the peak of COHb in the maternal blood, which also might be a result of a functioning placental barrier (Hill *et al*., 1977; Di Cera *et al*., 1988).

CO is a colourless and odourless gas produced from the partial combustion of organic material. Its binding affinity to human haemoglobin is some 200–300 times greater than that of oxygen; following the inhalation of CO emissions in confined spaces, the body does not receive sufficient oxygen and death occurs from internal asphyxiation. Even a carboxyhaemoglobin concentration in the blood of about 10–20% COHb causes symptoms of headache and dizziness, 30% COHb or more impairs cerebral function and results in lethargy, and about 60% COHb is likely to cause death in healthy people. A concentration of 0.05% CO in the air (equivalent to 500 ppm) can theoretically be assumed to give a carboxyhaemoglobin concentration of 50% COHb, depending on the person's physical activity, duration of exposure, and general state of health (Madea, 2006; Eckardt *et al*., 2011).

As the results of our experiments showed, small quantities of wood pellets also produce life-threatening levels of CO in confined spaces at a temperature of 26°C, associated with oxygen depletion. Similar experiments had already been carried out in the course of investigation of the deaths on the cargo ships, with comparable results.

In their investigation with stored wood pellets, Kuang *et al*. (2008) demonstrated that even small quantities of wood pellets can produce high CO concentrations and that the CO emissions are very temperature dependent. Peak CO emissions were quickly reached at high temperatures, whereas lower CO concentrations were produced more slowly at lower temperatures. Using quantities of 800–1200 g, they stored the wood pellets in airtight 2-l containers for a period between 42 and 56 days. CO emissions ranged from 13 973 to 15 086 ppm at 40°C and between 335 and 7662 ppm at 20°C. In their Bioenergie2020+ study, Emhofer and Pointner (2009) also showed that small quantities of wood pellets (2.2–6.5 kg) emit high concentrations of CO, depending on the available oxygen, the type of wood, and the temperature. The CO concentration increased exponentially, being 10–15 times greater with a rise in temperature from 15 to 40°C. Nevertheless, CO concentrations measured at a room temperature of 20°C were well over the maximum exposure limit (447 ppm). Kuang *et al*. (2008) determined that the CO concentrations in the containers were highest in those storing wood pellet fines, giving rise to the suggestion that an increased pellet surface area can boost the chemical processes responsible for CO emission. Emhofer and Pointner (2009) obtained similar results, determining that CO emission increased with greater mechanical abrasion of the wood pellets. In addition, there was a linear relation between the age of the pellets and CO production. Fresh pellets or pellets made of fresh sawdust produced higher gas concentrations than old pellets or pellets from old sawdust. With respect to storage times, Emhofer and Pointner (2009) demonstrated that wood pellets emit higher levels of CO in the first 6 weeks after production, which can be attributed to a diminishing fatty acid content of the stored wood. Studies by Arshadi *et al*. (2009) showed that the proportion of fatty acids in stored wood pellets decreases with time.

The chemical reactions responsible for CO production from wood pellets are assumed to be auto-oxidation processes, especially oxidation of the fatty acids to be found in wood (Kuang *et al*., 2008; Svedberg *et al*., 2008). As different types of wood contain different proportions of fatty acids, CO production from pellets also depends on the type of wood used. Pine contains a greater proportion of unsaturated fatty acids, which means that CO production from auto-oxidation processes in pellets made of pine is higher than that from pellets made of spruce (Emhofer and Pointner, 2009).

Other experimental series by Kuang *et al*. (2009) showed a relation between the remaining volume of air (headspace) and CO emission. Gas emission was greater from wood pellets when there was a large headspace, i.e. with a smaller pellet filling volume, as more oxygen was available for chemical processes per pellet, even if it took longer to reach peak emission. With respect to relative humidity, they determined only slightly increasing CO concentrations with higher relative humidities. Our experiments did not confirm this finding, which may be due to differences in the experimental set-up and method used for measurements. Kuang *et al*. (2009) placed a bowl of water in the container and took measurements every day; in our experiment the pellets were moistened with a fine jet of water, and the humidity was measured only twice. In other materials with high water content, such as wood chips and firewood, measurements made during transport by boat showed low CO concentrations (<100 ppm) in the air; this indicates that the different mechanisms responsible for production of CO, CO_2, and O_2 in the various materials depend on their water content (Svedberg *et al*., 2009).

Field measurements made in customer wood pellet stores by Emhofer and Pointner as part of the Bioenergie2020+ study (2009) showed that raised CO concentrations were to be found particularly in airtight pellet storerooms. The CO concentration was greater than 30 ppm (the maximum exposure limit in Austria) in 68% of the measurements and more than 1000 ppm in 9%. These measurements were made at least 6 weeks after the wood pellets had been filled into the storerooms, so that even higher CO concentrations were to be expected immediately after filling.

In summary, it can be said that CO is produced by auto-oxidation processes that depend on the available oxygen, the temperature, the age of the pellets, the type of wood used, and the filling procedures, as well as mechanical abrasion and the surface area of the wood pellets. Considering the pellet storerooms of private households, this means that there is an increased risk of life-threatening CO concentrations in winter, when the cold weather results in stores being replenished more frequently with freshly produced pellets or pellets that have been stored for only a short period. Because of the increased demand, manufacturers produce more wood pellets in the winter and store them for a shorter time than in the summer. This means that the emission of toxic gases in the end-consumer's storeroom will be higher in the winter; during the summer, these gases will have already been produced in the manufacturer's storerooms (Svedberg *et al*., 2004).

Both the deaths described in this paper and the fatal case from Ireland occurred in the winter months—in November and at the end of January and the beginning of February—when the demand for wood pellets is particularly high because of increased heating and hot water requirements. This may be due to the above mentioned reasons, but could also be a coincidence. At that time there might occur more technical problems, which have to be solved by people entering storage rooms and therefore suffering from off-gassing or oxygen depletion.

The DEPV (2011) and HS (2011) recommend that the storeroom is ventilated for 15 min before entering, by opening the main access door. This recommendation was also to be found on the warning sign (Fig. 2) affixed to the storeroom door in our second case. Our measurements at the scene showed that even after ventilation for 2 h, CO concentrations were still higher than 2000 ppm and thus in a range that is harmful to health and potentially life-threatening. Svedberg *et al*. (2008) have already remarked that it is not a good idea to leave the access door open, as this may be construed as an invitation to enter the pellet storeroom, especially if the warning sign is affixed to the outside of the door and can no longer be seen when the door is open, as in both our reported cases. This situation at the scene of the second accident resulted in a member of the recovery team experiencing typical symptoms of incipient CO intoxication, which highlights the problem. Svedberg *et al*. (2008) therefore recommend that a similar warning sign is also affixed to the inside of the access door and the doorway be equipped with a protective mesh to prevent anyone entering through the open door while the room is being ventilated. To ensure the safety of workers on cargo ships, they also recommend continuous ventilation of pellet storerooms and measurement of CO levels before entering, paying particular attention if the measured CO concentration is >35 ppm or secondary if no other toxic gas is present. In our opinion, these recommendations should also be made regulations for wood pellet storerooms in residential buildings. The current recommendations need to be urgently revised in order to prevent further deaths.

CONCLUSIONS

In conclusion, it can be said that life-threatening levels of carbon monoxide can arise from wood pellets kept in storerooms, not only at high temperatures but also at average room temperature, with a large headspace, by freshly produced and/or recently filled pellets, and at the humidity usually found in these storerooms. The danger seems to be greater in the winter, when the increased demand for pellets results in the more frequent replenishment of freshly produced pellets and more technical problems with the wood pellet heating system might occur. Entering wood pellet storerooms in residential buildings carries a risk that has previously been underestimated. This paper is the first scientific report including a review of the literature of two deaths from CO poisoning due to wood pellets in storerooms of private households, occurring within the space of a year. In our opinion, the recommendations of the wood pellet industry are inadequate; ventilating the storeroom for 15 min by opening the access door is particularly unsatisfactory. Immediate efforts are needed to ensure the continuous ventilation of such storerooms. In addition, warning signs should be obligatory, not just recommended, and affixed to both the outside and the inside of the main door. A protective mesh should be provided across the doorway and the CO and O_2 levels measured with an appropriate device before entering the room. The danger of CO poisoning should be specifically explained to people who may have to enter wood pellet storerooms in the case of a malfunction, and they should receive special safety training for this event. If such changes are not made, we consider that there is a risk of further deaths in the wood pellet storerooms of private households, especially during the winter months.

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