PENTACHLOROPHENOL IN INDOOR AIR:
SEALING EXPOSED PRESSURE-TREATED WOOD AND
IMPROVING VENTILATION TO REDUCE AIRBORNE CONCENTRATIONS

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Summary

Pentachlorophenol (PCP) is a widely used biocide. It is used in buildings as a wood preservative and as a fungicide in finish materials. Exposure of the general population to trace concentrations is routine. PCP has been found in low concentrations in food, indoor air, many common consumer items, and on the surfaces of playground furniture and other outdoor uses of wood. The severe toxicity of some commercial PCP contaminants has resulted in efforts to limit population exposures to PCP used indoors. The United States Environmental Protection Agency has recently restricted PCP use in buildings.

In a large office building containing PCP-treated timbers, sealing exposed surfaces of treated wood reduced PCP air concentrations from 2.5 to 0.5 ppb. Improved ventilation further reduced air concentrations to 0.3 ppb, substantially lower than acceptable levels established by public health officials' risk estimates. Increased body burdens have been found in a sample of the building's occupants. Recently, the integrity of the sealant appears to have been destroyed and cracks in the beams have appeared. Further research is necessary to determine the durability and impenetrability of applied sealants and to establish guidelines for maximum acceptable indoor PCP air concentrations.

Introduction

Pentachlorophenol (PCP or "penta") is a significant indoor air pollutant due to its widespread use in construction, agriculture, and consumer products; the increased body burdens observed in individuals exposed to even very low airborne concentrations; and the severe toxicity of common contaminants of commercial PCP formulations. Wood preservation alternatives do not present the attractive features of PCP - paintability of treated wood, neutral effect on wood color, and durability.

Human Exposure to Pentachlorophenol

Use of Pentachlorophenol. PCP is used as a pesticide, herbicide, and fungicide worldwide. Annual production is estimated at 110 million pounds, 51 million pounds in the USA (1). General population exposure is substantial. Human exposure to PCP results from residues in food and trace amounts in water; from exposure in buildings containing PCP-treated wood or other materials; from exposure to PCP in numerous consumer products such as paper, cleaning products, soaps, skin medication, leather and cotton; and, from PCP formation as a metabolite of many common pesticides (1-4). Table 1 lists the major registered PCP uses in the USA. Useage is similar in Great Britain (1).

USE	PRODUCTS
Fumigant	Shipping-van interiors
Herbicide	Non-food vegetation control
	Forage seed crops
Insecticide	Wood
	Beehives,
	Seed plots, greenhouse use
Microbiocide	Burlap
	Canvas
	Cotton
	Leather
	Rope
	Twine
	Wood
Microbiostat	Commercial and industrial water cooling
Postharvest wash	Fruit
Preservative	Oil and water-based paints
	Hardboard
	Particle-board
Slime control	Pulp and paper products

Table 1. Major Registered Uses of Pentachlorophenol in the USA (Crosby, 1981)

Occurrence in humans. In a sample of the U.S. population, 85% had urine PCP averaging 6.3 ppb (5). In Hawaii, where PCP use is more prevalent due to the need for wood protection against pests and fungii in the humid, warm climate, residents have average blood and urine concentrations approximately seven times those of the general U.S. population (1).

It is believed that exposure occurs through inhalation, ingestion, and, to a lesser degree, absorption through the skin. Drinking water and food residues are considered the likely sources for general population exposure (1,3). Individuals living or working in buildings where airborne concentrations are elevated above background levels may inhale or absorb the excess amounts found in their blood and urine.

There is no established maximum acceptable concentration for PCP indoors in non-occupational environments. The U.S. threshold limit value (TLV) for industrial workplaces is 0.046 parts per million (6). Increased body burdens (elevated blood serum and urine levels) have been found in occupants of homes where PCP air concentrations were only 0.02 - 0.04 ppb, less than 0.1% of the industrial TLV. No adverse health effects were reported (6,7).

Urine PCP levels in a sample of office workers occupying the PCP-contaminated building (described below) rose significantly after they moved into the building. Air PCP levels were in the 0.46 - 1.38 ppb range in that office building (8).

Human health effects have been observed in occupants of residences with PCP air concentrations from 0.9 - 2.8 parts per billion (9). The author has investigated PCP contamination of a home where two adult occupants were severely sensitized after exposures to PCP emanating from a small area of treated wood in the basement. Contamination of the first and second floors of the two-story house appears to have occurred while the forced-air, gas-fired furnace or attic-mounted "whole house fan" were operated during the heating and cooling seasons respectively. PCP air concentrations of 0.23 ppb were obtained at the basement stairway without either fan or furnace operating.

Such incidents and the severe toxicity of some commercial PCP contaminants have resulted in efforts to limit population exposures to PCP used indoors. The United States Environmental Protection Agency has recently restricted PCP use in buildings (10).

	Family members (n = 5)	Controls (n = 42)
Ages:	2 - 34	9 - 65
Serum PCP (in ppb)	580 - 1,750	3 - 67.9
Urinary PCP (in ppb)	23 - 216.0	0.7 - 11.0

Table 2. Pentachlorophenol serum and urinary levels in residents of a PCP-treated log home in Kentucky (Center for Disease Control, 1980)

Toxicity of pentachlorophenol.

The common impurities of PCP which include dioxins, furans, and hexachlorobenzene, are considered the sources of PCP toxicity for chronic exposures (10). Commercial PCP is considered fetotoxic and teratogenic. PCP has been shown to cause fetal death and embryotoxicity in laboratory animals. No safe level for exposure of PCP to pregnant women has been established (11).

The health consequences of exposures to PCP in indoor air are not well understood. The lethal dose of PCP for 50% of test rats exposed by inhalation is 8% of the oral dose, and 4% of the dermal dose (1,3). This indicates the potential significance of exposure to PCP in indoor air.

Pentachlorophenol use in buildings.

Eighty percent of U.S. PCP consumption is as a wood preservative (1,4). While much of the annual use of preserved wood is for utility poles (40 million cubic feet), PCP is used extensively for treatment of lumber and timber (20 million cubic feet) and fence posts (10 million cubic feet) (1). PCP use in buildings is widespread: to treat foundation and structural lumber and timber, to protect structural members exposed to the weather, and to preserve finish materials and coatings. PCP use is common in residences, offices, schools, churches, gymnasia, and other structures utilizing exposed wood structures which extend outside the perimeter walls. PCP is used in paints, wood stains and sealers (1,4).

Determinants of PCP indoor air concentrations.

Sauer and co-workers reported sampling a variety of building types, conditions and PCP uses. The results indicate that ventilation is the most important determinant of PCP concentrations. They could not distinguish the individual effects of temperature, humidity and PCP application solvent, although these factors were determined to influence airborne PCP levels. In only one of eleven structures monitored by Sauer was a relationship established between PCP vapor levels and treated-wood-surface-area-to-room-volume ratio (12).

Control of PCP indoor air concentrations. In a newly-completed, central California office building constructed with PCP dip-treated, glu-laminated timbers exposed on the interior, occupants complained of irritation and respiratory illness. Application of brush-applied polyurethane varnish and increased use of natural ventilation resulted in decreased complaints. A larger office building requiring more extensive remedial work is described below.

Experimental work

Background

A state office building in coastal southern California was the subject of extensive air sampling and remedial work related to PCP. The four story structure contains 156,000 sq. ft. (14,500 sq. meters) of conditioned floor area, 1,720,000 cu. ft. (50,750 cu. meters) of conditioned volume. The structural system consists of glu-laminated Douglas fir columns, girders and purlins. To conserve energy, extensive glazing provides daylight on the interior. Some of the structural wood extends outside the exterior walls to support an elaborate sun shading system which reduces direct sun entry. The beams and columns were left exposed on the interior as well as the exterior.

Forty percent of the interior horizontal structural members extend outside and were PCP pressure-treated (see Table 4). PCP treatment was by the Cellon process (gas carrier) for wood beams installed in the first floor and the remainder was treated using an oil carrier. A sample of surface material from the treated wood contained 0.185 percent (1850 ppm) PCP by weight, a normal concentration of preservative.

TYPE OF BUILDING	AGE OF BLDG. (YRS)	VENTI-LATION	PENTA CARRIER	WOOD/AIR VOL. RATIO ($M^2/100M^3$)	TEMP. RANGE (°C.)	PENTA CONC. (ug/m^3)	DATA SOURCE
Office/lab							
- basement	4	Low	A	72.1	21	38.0	(1)
- main floor	4	Medium	A	0.0	21	8.8	(1)
Office	1	Low	A	16.0	21	30.7	(2)
Office	1	Low	A	16.0	25	27.7	(2)
Warehouse	6	Medium	A	8.8	11	3.52	(1)
Warehouse	9	High	A	24.6	15-24	0.10	(1)
Research barn	-	Medium	A	6.2	16	0.52	(1)
Pole barn (enclosed)							
- main area	5	High	A	16.8	17-27	0.04	(1)
- nursery	5	Medium	A	56.3	17	0.88	(1)
House - basement	1	Low	B	0.3	21-27	1.0	(1)
House	3	Low	C	22.6	23	0.28	(1)
Log home	1	Medium	C	36.0	18-29	0.11	(1)
Log home	1	Medium	C	40.3	18-28	0.38	(1)
Log home							
- first floor	5	Low	C	n.a.	n.a.	0.20	(3)
- second floor	5	Low	C	n.a.	n.a.	0.38	(3)
Greenhouse	11	High	A	15.7	18-28	0.09	(1)
Natatorium							
- pool room	2	Medium	D	12.8	28	0.33	(1)
- mechanical room	2	Medium	D	10.5	28	0.14	(1)

Penta carriers: A = P9 Type A, B = Woodtreat TC gel, C = Mineral spirits, D = Methylene chloride

Sources: (1) Sauer, 1982; (2) Table 2; (3) CDC, 1981

Table 3. Airborne Pentachlorophenol levels in treated wood structures. After Sauer, 1982; Reference (12).

Member:	Purlins	Girders: 2@ 1.4 m o.c.	Total
Dimensions (cm)	27.3 x 38.1	27.3 x 76.2	
Spacing (m)	1.37	9.45	
PCP-treated wood			
Wood surface/ Interior volume ratio*	11	5	16
% Surface sealed	60	100	72.5

* ($m^2/100m^3$)

Table 4. Data on Wooden Beams in Office Building

Discoloration, "blooming" of PCP crystals, and exuding pitch on the surface of treated wood were deemed visually unacceptable. Cleaning was attempted using a solvent containing aromatic hydrocarbons (88.9%), aliphatic hydrocarbons (5.2%) and ethanol (5.3%). Hot water washing and brush scrubbing were completed and deemed inadequate to allow the wood to be left with a "natural" finish. A wood stain (containing PCP as a biocide) was applied to impart a dark, finish to the wood.

During the process of considering methods to improve the appearance of the discolored beams, a PCP manufacturer informed the architects that indoor use of penta presents potential health hazards. Pre-occupancy indoor air quality was being monitored in several new, energy-efficient state office buildings, including the one which contained the PCP-treated wood. So PCP was added to the substances collected and analyzed.

Building ventilation. The building's office spaces are ventilated and cooled by eight roof-mounted units serving vertical zones. The restrooms, cafeteria and auditorium are separately ventilated. Maximum design supply rates are 1 cfm/sq ft. This results in 5.2 Air Changes per Hour (ACH) at 100% supply and outside air conditions. Normal operation introduces approximately 16 percent outside air with VAV supply rates from 50 to 100% of design values. Actual hourly outside air exchange rates vary from 0.6 to 1.1 under normal conditions and 2.6 to 5.2 with 100% outside air conditions. Some return air registers collect air from more than one supply zone, combine it and return it to the rooftop units. Heating is by fan coil units located in perimeter zones only and mounted just below the

A number of problems in the design, installation and functioning of the mechanical ventilation system (HVAC) were found in the course of the air sampling and remedial work. These included improper system balance, potential entrainment of exhaust air in the supply train at the rooftop, total damper closures at some supply VAV boxes, many defective thermostats, incomplete static pressure control system adjustment, and others. Many of these were corrected during the PCP-related investigations and remedial work.

Environmental monitoring program. Air sampling was conducted at several stages according to the original indoor air quality monitoring plan. The plan called for sampling without ventilation during construction after carpet installation; with ventilation after the mechanical ventilation system was completed, balanced and operating; and after occupancy of the completed building. Typical indoor pollutants were measured. Levels were typical of new office buildings and comparable to several other new state office buildings. PCP was collected in response to the advice of the chemical manufacturer as mentioned above. PCP levels were deemed unacceptably high, and a remedial program was initiated. Additional sampling related to the PCP evaluations and remedial work were added after the second round of sampling.

PCP sampling methods. Personal monitoring pumps were used to collect samples in midget impingers filled with ethylene glycol and submitted to the laboratory for analysis by NIOSH-approved methods. Sampling times ranged from 3 to 8 hours at 0.7 liters/minute and were usually taken one per location. Some duplicate samples were submitted to the State of California Air Industrial Hygiene Laboratory for validation of results. Ventilation was manipulated to obtain "worst case" and "normal" conditions.

Results.

Pre-remedial air samples contained PCP concentrations of 2.8 ppb without ventilation and 2.5 ppb with very low ventilation. Acceptable concentrations for PCP in indoor air have not been established for non-industrial workplace exposures in the USA. However, there was agreement among public health officials contacted by the author that concentrations above 2.8 ppb were likely to result in complaints of irritation and effects on upper respiratory functioning.

The unavailability of useful standards for non-industrial indoor air contributed to a significant time delay in building occupancy while potential effects were investigated and remedial work was performed. A health risk assessment by state health officials established a maximum acceptable level at 1.84 ppb (20 micrograms per cubic meter) for the state office worker population. Evaluation of air sampling results and discussions with public health officials resulted in the initiation of remedial work.

Methods of sealing PCP-treated wood were investigated. Data on sealing wood pressure-treated with penta in methylene chloride to reduce PCP vaporization was limited to chamber tests using 3/4 in. x 3 in. x 11 in. samples. These tests indicated that polyurethane varnish was 93 to 96% effective in reducing emanation rates in a small chamber test (13). Subsequent testing (results were not available in 1982) indicated that one coat of polyurethane varnish was 70 percent effective in reducing emanation rates from wood treated with penta in P9 type oil carrier such as that used in the subject building.

The sealant's efficacy was tested in selected locations within the building. Two coats of polyurethane varnish were spray-applied only to exposed areas of treated wood. Portions of the purlins above the ceiling could not be economically or quickly sealed. To do so would have required removal of the ceiling. Therefore, it was decided to seal the exposed portion (60% of the total surface area) of treated wood with the varnish (Fig. 1). Air samples from unventilated spaces with sealed wood 13 days after application of the sealant indicated a threefold reduction in PCP compared with unsealed wood. Air concentrations in a low-ventilated space containing unsealed wood resulted in concentrations similar to unventilated spaces containing sealed wood. It was decided to seal exposed surfaces of treated interior wood members with two spray-coats of polyurethane varnish.

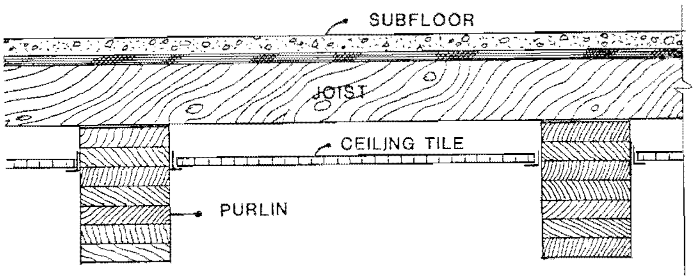

Figure 1. Cross-section through purlin showing position of ceiling and concealed portion of beam above it.

Twelve days after the second sealant coat was applied throughout the building, 4 consecutive days of testing (10/29-11/1) under varied ventilation conditions confirmed the efficacy of the sealant. An average of 0.5 ppb PCP was found in 68 air samples. Ventilation rates (estimated) ranged from 0.8 to 5.2 outside ACH. Defective HVAC functioning was detected, and the necessary ventilation equipment corections were made. Further testing (11/17) found PCP levels of 0.3 ppb at normal ventilation rates (1.1 ACH). On this date, one HVAC unit was still malfunctioning. Subsequent tests (02/07/83) at different locations found 0.7 ppb average PCP levels at an average 1.6 ACH.

Measurements of air and wood surface PCP concentrations in the Spring and Summer of 1984 and visual inspection of the beams in October, 1984, indicate that the sealant is not adequately

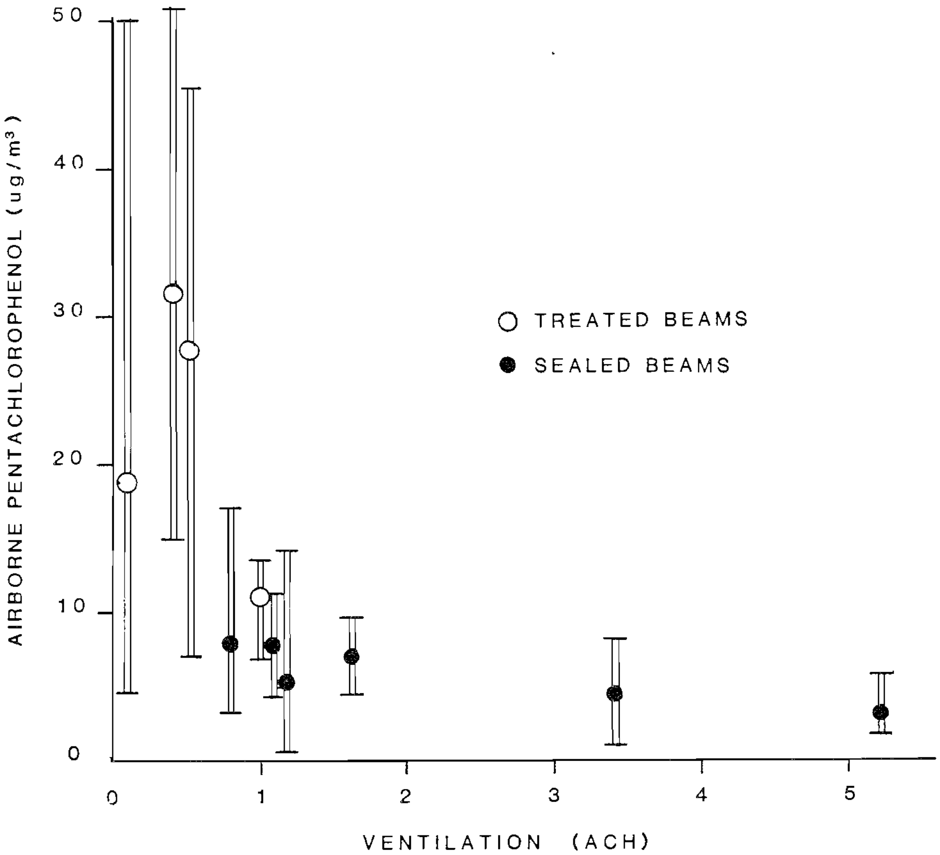

Figure 2. Pentachlorophenol concentrations and ventilation -- air changes pre hour -- for locations with treated and sealed beams in southern California office building.

controlling PCP emanations. Cracks have developed in the bottom surface of many beams, and PCP crystals have been seen within the cracks.

Discussion

PCP concentration determinations in indoor air

Gebefugi explored the effects of temperature and absolute humidity on PCP concentrations in indoor air. Investigations conducted in a test room lacking controlled ventilation did not adequately address the impacts of ventilation on experimental results. The results were inconclusive, although the effect of temperature was clearer than that of water vapor (14). Sauer found ventilation to be the dominant factor affecting airborne PCP concentrations (12).

Results compared to predicted values
Theoretical values were calculated as equilibrium concentrations (Raoult's Law) of PCP in room air based on measured concentrations in the treated wood (1850 ppm) over the observed temperature range during sampling (20-28 ^{o}C). The calculated values are 0.3 - 1.1 ppb compared with 0.3 - 3.5 ppb measured values. The deviation might result from inter-room variations in wood PCP content, ventilation or temperature. Higher temperatures at the ceiling than in the sampling zone would increase PCP vapor pressure.

Effect of ventilation rates, temperature and relative humidity. Ventilation rate estimates were made based on measurements of air volumes delivered at distribution registers and observations of positions of intake and exhaust vanes at rooftop units. Variations during the testing days and from unit to unit were observed to be substantial. Therefore, ventilation rate estimates should be interpreted cautiously.

Ventilation rate data suggest a strong relationship between PCP concentrations and ventilation (Fig. 2). Variations from an ideal relationship might be explained by the effects of temperature, inter-room differences, and errors in the ventilation rate estimates.

The aggregated data do not support a strong relationship between temperature and PCP air concentrations, although the range is reasonably consistent with the theoretical values based on temperature (Fig. 3). No clear relationship to relative humidity is evident. This would be expected due to the low water solubility of PCP.

Date	PCP Conc. (ppb) #	Range	Mean	Temp °C	R.H. %	HVAC System ACH[b]	Units[c]	VAVs[d]	Beams[a]
02/19/82	6	1.4-4.6	2.8	21	51	0.4	Off		Treated
06/04/82	7	0.7-4.1	2.5	25	54	0.5	On	Variable	Treated
09/09/82	7	0.4-2.4	1.0	25	64	0.1	Off		Treated
09/12/82	2	2.3-2.7	2.5	25	62	0.1	Variable	Variable	Treated
09/23/82	6	9.2-1.2	1.1	24	54	0.1	Off		Sealed
	3	2.9-4.5	3.5	24	55	0.1	Off		Treated
	3	0.9-1.2	1.0	23	54	n.a.	Variable	Malfunct	Treated
09/24/82	6	0.7-1.3	1.0	23	66	1.0	Variable	Variable	Treated
	6	0.4-1.1	0.7	23	66	1.0	Variable	Variable	Sealed
10/29/82	15	0.1-0.8	0.4	23	48	3.4	Open	Minimum	Sealed
	5	0.3-1.4	1.0	24	48	n.a.	Open	Malfunction	Sealed
10/30/82	6	0.2-0.5	0.3	23	61	5.2	Open	Maximum	Sealed
	2	0.6-0.8	0.7	23	66	n.a.	Open	Malfunction	Sealed
10/31/82	19	0.3-1.3	0.7	24	59	1.1	Minimum	Maximum	Sealed
	1	0.9	---	24	65	n.a.	Minimum	Malfunction	Sealed
11/01/82	18	0.3-1.6	0.7	26	61	0.8	Variable	Variable	Sealed
	2	1.0-2.4	1.7	27	55	n.a.	Variable	Malfunction	Sealed
11/17/82	18	0.1-0.8	0.3	23	57	1.1	Variable	Variable	Sealed
	2	0.7-1.3	1.0	27	54	n.a.	Variable	Malfunction	Sealed
02/07/83	6	0.4-0.9	0.7	23	56	1.6	Variable	Variable	Sealed

(a): Treated = PCP Pressure-Treated; Sealed = Polyurethane Sealed
(b): ACH = Air Changes Per Hour (Outside air delivered to interior spaces)
(c): Units = Rooftop-mounted air handling units
(d): VAVs = Variable Air Volume Units within space

Table 5. Airborne Pentachlorophenol, temperature, relative humidity and ventilation in southern California office building.

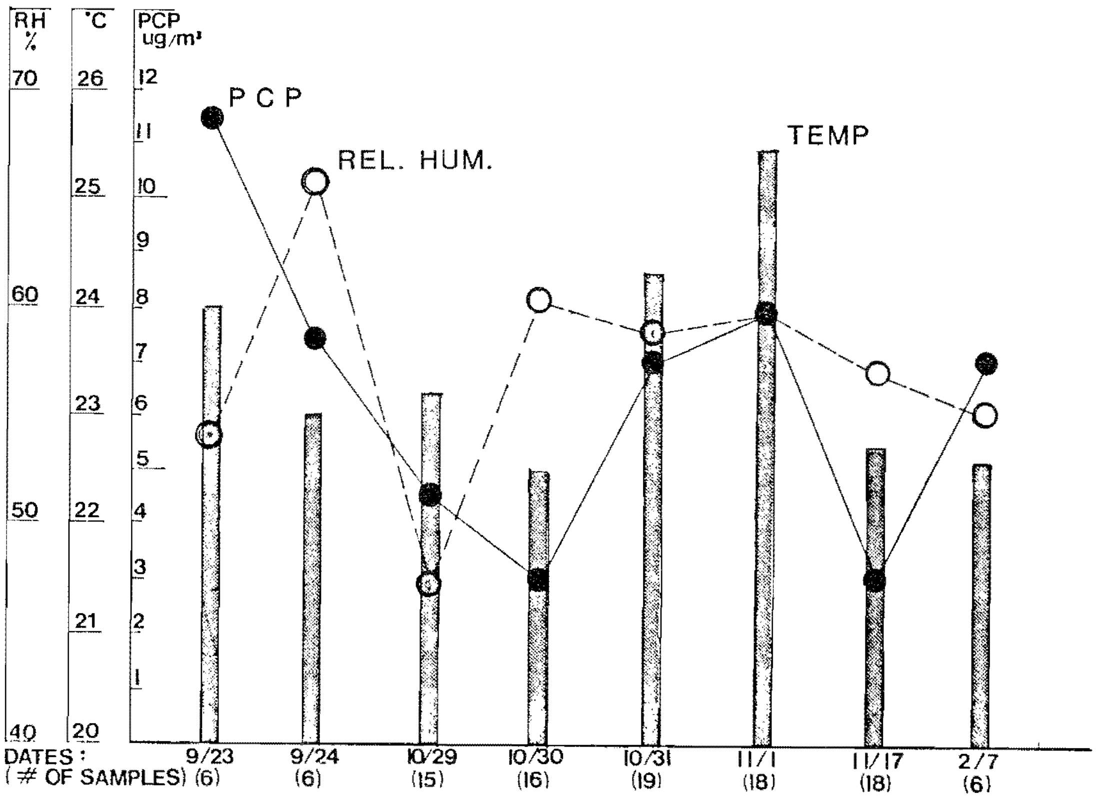

Figure 3. Pentachlorophenol concentrations, temperature and relative humidity in southern California office.

Conclusions

1. Use of Pentachlorophenol-treated wood indoors should be limited to essential purposes and only where alternatives are clearly unacceptable. Treated wood should be sealed before the wood is installed, particularly where all or part will be concealed by finish construction.

2. Sealing PCP-treated wood can be effective in reducing airborne concentrations. Polyurethane varnish appears suitable but the duration and extent of its effectiveness have not been determined and should be investigated further.

3. Ventilation appears to be effective in reducing airborne PCP levels.

4. Ventilation data is significant in interpreting air sampling results due to the wide variability of actual air change rates in the field, particularly in newly-constructed buildings. Air change rates and ventilation are important determinants of contaminant levels and should be considered routinely during air sampling as well as during building design.

5. Further research on PCP air concentration determinants in buildings should include characterization of ventilation rates, the effects of temperature and humidity, surface material PCP concentrations, and the absorption of PCP on the surfaces of building contents.

6. Acceptable air concentrations for PCP in non-occupational indoor air should be established for non-industrial exposures in the USA.

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