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Permanency of Boric Acid used as a Fire Retardant in Cellulosic Insulation

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ABSTRACT

The rate of loss of the chemical fire retardant, boric acid, from loose-fill cellulosic insulation due to sublimation has been determined. Apparent sublimation pressures for boric acid have been measured as a function of temperature and relative humidity using a flow system. A direct determination was also made of the rate of mass transfer of boric acid in cellulosic insulation to the air above the insulation. These data were used in a numerical model to show that the loss of boric acid from cellulosic insulation is insignificant at 70 °C and relative humidity near 100%.

The redistribution of boric acid and borax in a commercial cellulosic insulation due to vibration was studied by analyzing specimens taken from the top and bottom of horizontally applied material. Long periods of vibration failed to result in statistically significant chemical redistribution.

INTRODUCTION

Cellulosic insulation is one of the oldest thermal insulations still in common use today. Loose-fill and spray-applied cellulosic insulations are used extensively in the walls and attics of residential and commercial buildings. Cellulosic insulation is manufactured from recycled newsprint or cardboard and treated with fire-retardant chemicals to reduce its combustibility.

In the past there have been fires where cellulosic insulation was reported as the first material ignited when it was improperly installed [1, 2]. It has also been demonstrated in the laboratory that some types of recessed light fixtures can ignite cellulosic insulation when the fixtures are overlamped and covered with insulation [3]. As a result, in 1978, the U.S. Congress made it mandatory that all cellulosic insulations meet minimum standards for flame resistance. The test methods that resulted were the critical radiant flux test and the smoldering combustion test [4, 5]. In order to pass these tests, cellulosic insulation must include a significant amount of chemical fire retardant in the product. These chemical fire retardants are expected to be effective not only at the time of manufacture but also for the life of the structure in which they are installed. Thus, the permanency of the retardant chemical becomes an important consideration. Boric acid and sodium borate (borax) are two fire-retardant chemicals commonly used by manufacturers of cellulosic insulation [6, 7]; therefore, discussions concerning the long-term presence of boric acid in cellulosic insulation have been underway for many years [8 - 12].

A review of the literature, however, has shown that physical properties such as sublimation pressure necessary to discuss permanency have not been unequivocally determined [13 - 20]. Concern about the sublimation of pressure may be traced back to 1937, when Stackelberg *et al.* [21] apparently reported steam distillation results. Figure 1 shows results obtained by Stackelberg and a sublimation pressure measurement completed to confirm that Stackelberg's data were for boric acid in a steam environment. Insulation installed in buildings is not generally exposed to temperatures above about 70 °C. Sublimation data for boric acid at temperatures at or below 70 °C were not found in the literature.

Boric acid and borax are stable inorganic chemicals that will not decompose at the temperature levels normally encountered in

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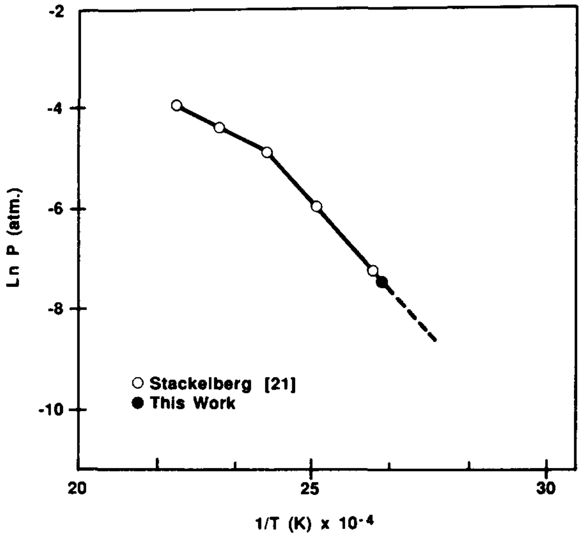

Fig. 1. Experimental results for the apparent vapor pressure of boric acid in steam.

attic spaces. A loss of retardant effectiveness means, therefore, either a loss of chemical or a change in the combustibility of the cellulosic fiber. For the present discussion, a lack of permanence means either that fire retardant has been transported away from the insulation or that redistribution of the chemical has left regions in the insulation with insufficient fire retardant.

Several possible loss mechanisms can be identified for boric acid. Cellulosic insulation manufactured by a dry process does not result in chemical bonding between the boric acid and the insulation. There has been speculation in the past that vibration of a building structure could separate boric acid from fiber and result in some redistribution of the boric acid in the insulation. Sublimation and transport of boric acid from the porous insulation to surrounding air is a second possible loss mechanism. Excessive condensation of water within cellulosic insulation can result in a redistribution of fire retardant or even leaching chemical out of the insulation. Finally, some separation of chemical and fiber may occur during shipping and installation.

Two of the four possible loss mechanisms mentioned above were studied. A mechanical vibration test was performed to address the redistribution question. Mass transfer of solid boric acid from cellulosic insulation to bounding air was measured in order to address the sublimation question.

MECHANICAL VIBRATION TEST RESULTS

The dry blending process used in the manufacture of cellulosic insulation does not result in chemical bonding between boric acid and insulation. The speculation that vibration of a structure containing cellulosic insulation could result in chemical redistribution has been examined with the result discussed in the following paragraphs that no significant redistribution was observed.

A metallurgical lapping-polishing machine was used to vibrate insulation specimens at 60 hertz with a vertical displacement of approximately 0.076 mm to test for possible chemical redistribution. A test box 30.5 × 30.5 × 16.8 cm^3 was made of 19-mm-thick plywood. The test box was divided into four sections separated by thin metal sheets. The insulation to be tested was processed through a commercial blowing machine prior to the vibration test. The insulation that was tested was a commercial product with a label value for the settled density of 41.6 kg/m^3. The vibration test was performed on insulation initially at a density of 35.0 kg/m^3.

The cellulosic insulation to be tested was blown into the test box through 30.5 m of 6.35 cm diameter hose. After manually smoothing the surface with a straight edge, the test box was securely attached to the polishing machine. After 168 hours of vibration, two samples were taken from the top and bottom of the outermost section leaving the remaining sections untouched. After time increments of 168 hours the procedure was repeated. Samples were taken at 168 hours, 336 hours, 504 hours, and 672 hours from the same test box. Water-soluble chemicals were leached from the top and bottom samples and analyzed for boron and sodium using inductively coupled plasma (ICP) and the atomic emission spectrometric method for trace element analysis of water and wastes [22]. The experimental results for boron and sodium content are shown in Table 1. The ratio of concentrations at the top and bottom should be close to one if there is no separation of chemicals. The ratios calculated from the data in Table 1 are shown in Table 2.

The results in Table 2 show relatively small deviations from one. The ratios in Table 2 were compared with a set of chemical analyses performed on a larger sampling of

TABLE 1

B and Na analyses for one cellulosic insulation subjected to vibration

Time (hours)	Top			Bottom		
	B (ppm)	Na (ppm)	Total chemical (Wt. %)	B (ppm)	Na (ppm)	Total chemical (Wt. %)
0	296	348	24.0	311	366	23.8
168	309	361	23.0	287	344	23.9
336	288	342	24.2	292	346	24.1
504	290	361	23.7	301	348	23.9
672	290	359	24.0	284	361	23.9

B or Na content of an aqueous solution made by contacting five grams of insulation with water.

TABLE 2

The ratio of boron and sodium concentrations at the top and bottom of specimens subjected to vibration

Time (hours)	Concentration ratio (Top/bottom)	
	B	Na
0	0.95	0.95
168	1.08	1.05
336	0.99	0.99
504	0.96	1.04
672	1.02	0.99

the same product to assess the statistical significance of the observed differences. Nine specimens of insulation taken from a 20 m^2 region of 15-cm-thick blown insulation were analyzed for B and Na to obtain an estimate of the variance to be associated with sampling and analysis. The mean concentration (C) and standard deviation (σ) for the set of nine samples were 283.0 ppm and 3.14 ppm for boron and 364.1 ppm and 3.44 ppm for sodium, respectively. The results from Table 2 and the variances determined above were used to construct the bounds shown in Figs. 2 and 3. From these observations, it was concluded that significant boric acid or borax redistribution due to vibrations did not occur.

A paper by the National Association of Home Builders (NAHB) [23] postulates that one hour of 15 hertz vibrations at 0.051 mm peak-to-peak displacement simulates one year of *in-situ* exposure. Using the NAHB figures, 0.076 mm peak-to-peak vibration at 60 hertz for 672 hours would be equivalent to more than 672 years of *in-situ* exposure.

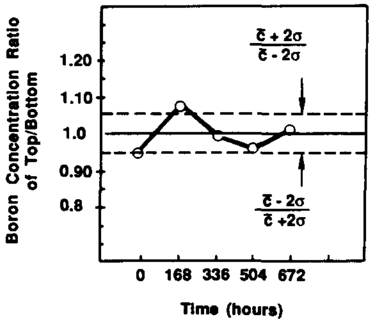

Fig. 2. Ratio of top to bottom B content for specimens of loose-fill cellulosic insulation subjected to vibration.

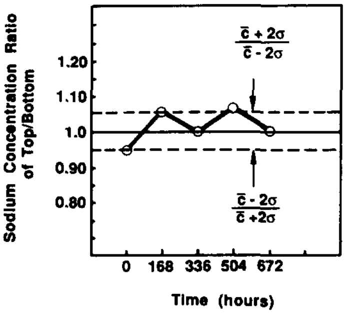

Fig. 3. Ratio of top to bottom Na content for specimens of loose-fill cellulosic insulation subjected to vibration.

SUBLIMATION STUDIES

The calculation of mass transfer rates for boric acid from attic floor insulation to ambient air requires sublimation pressures and diffusion coefficient data. The sublimation pressure of boric acid was determined in this work by a flow method [24]. The diffusion coefficient for boric acid in air was determined from a measurement of the loss of boric acid to air flow in a square duct. These experimental data were then used to calculate loss rates of boric acid from cellulosic insulation as a function of temperature, humidity, and the airflow rate.

The measurement of boric acid sublimation rate was accomplished by air flow through a controlled temperature system then into contact with boric acid. Because of the low airflow rate, the air leaving the contactor (illustrated in Fig. 5) was saturated with boric acid. Saturation was verified by reducing the airflow rate until constant boric acid concentrations were observed. The air saturated with boric acid was bubbled through water and the boric acid contained in the air was dissolved in the water. The water was subsequently analyzed by ICP for boron content. A schematic arrangement of the apparatus used to determine sublimation pressure is shown in Fig. 4. Two processes were used to control the humidity of the air. For low humidity measurements, the supply air was passed through a plastic cylindrical dryer 6.7 cm in diameter and 29 cm long. The dessicant used was a mixture of anhydrous calcium sulfate with cobalt chloride. For measurements under high humidity conditions, water vapor and air were mixed to produce the desired humidity. This was accomplished by passing known quantities of air (measured by a calibrated flowmeter) through a stainless steel tube submerged in a controlled temperature bath. Two wet test meters were used as shown in Fig. 4 to measure the total volumetric flow rate of air.

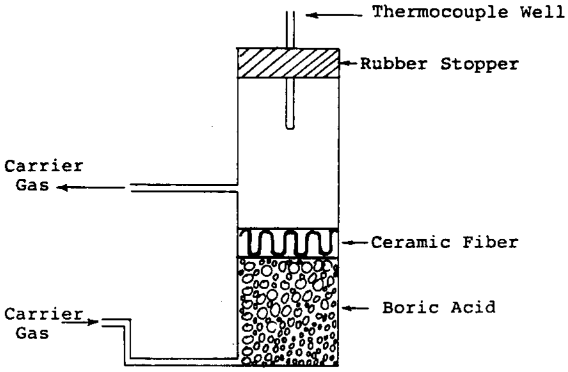

Fig. 5. Diagram of contactor used for the measurement of the sublimation pressure of boric acid.

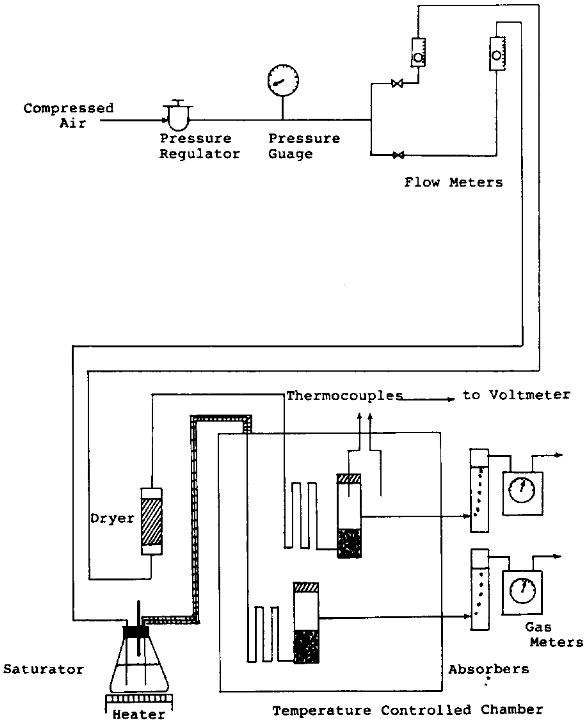

Fig. 4. Diagram of apparatus to measure the sublimation pressure of boric acid in air.

The outlet of the flowmeter shown in Fig. 4 was connected to a preliminary heating tube which was about 1.32 m of 9.52 mm i.d. flexible tubing and then to the contactor. The contactor shown in Fig. 5 was a copper cylinder 17.8 cm high and with an inside diameter of 3.51 cm. The heated air entered the contactor from the bottom and exited from the outlet nozzle which is about 8.9 cm from the bottom. Boric acid was placed in the contactor to a depth of approximately 7.6 cm with ceramic fiber above it to prevent loss of solid particles. An outlet tube connected to the contactor led to an absorber system. The preliminary heating tube, the contactor and the outlet tube were housed in an environmental chamber.

The trap system was an absorber which is a 6.67 cm i.d. and a 29.9 cm high cylinder constructed of acrylic plastic containing distilled water. The outlet air stream from the heating chamber was bubbled through the absorber. Sublimation pressure was calculated using eqn. 1.

$$P_1 = P_2 n_1/(n_1 + n_2) \tag{1}$$

where

P_1 = sublimation pressure of substance being studied;

P_2 = pressure of carrier gas;

TABLE 3

Summary of experimental apparent vapor pressure data for boric acid

Temperature (°C)	Duration of run (hours)	Carrier gas (% RH air)	Apparent vapor pressure (Pa)
90	786.5	100%	16.16
90	634.0	100%	15.08
90	786.5	0.5%	0.173
90	465.0	0.5%	0.147
70	816.0	100%	<0.012
70	816.0	0.5%	$<9.87 \times 10^{-3}$
20	2010.0	100%	$<9.60 \times 10^{-4}$
20	2010.0	0.5%	$<1.87 \times 10^{-3}$

n_1 = number of moles of boric acid in the absorber (trap);
n_2 = number of moles of carrier gas.

A summary of the experiment results is shown in Table 3. At 20 °C and 70 °C the sublimation pressure was below 0.0123 Pa (9.2×10^{-5} torr). At 90 °C the vapor pressures were 0.1600 Pa (0.0012 torr) and 15.63 Pa (0.1172 torr) for 0.5% and 100% relative humidity, respectively. The measurement of the sublimation pressure at low temperatures requires long time periods to reach the detection limit of 0.005 ppm in the absorber. The detection limits were not reached in 2010 hours of flow at 20 °C or 816 hours of flow at 70 °C. The B detection limit was used to calculate the upper bound for the sublimation pressure of boric acid at 70 °C and below.

THE DETERMINATION OF THE DIFFUSION COEFFICIENT FOR BORIC ACID IN AIR

Two different experiments were conducted on the evaporation of solids and liquid into fully developed laminar flow streams. A measurement of the diffusion of water into a nitrogen stream was used to check the model developed later in this Section. The data for mass transport of boric acid into air were used to evaluate the diffusion coefficient for boric acid in air.

The apparatus used to accomplish this experimental work consisted of a gas supply system, a heating system which includes a mass transfer cell and a trap system. A diagram of the apparatus is shown in Fig. 6. As shown in the Figure, the boric acid/air and water/nitrogen transfer measurements used the same heating system which was made from square steel duct. The duct formed an entrance and exit from a mass transfer cell containing the solid phase material to be tested. It was 5.03 m in length and 7.3 cm in width. Approximately 2.44 m of the duct formed the inlet while the remaining length was the exit section. These relatively long entrance and exit lengths were used to

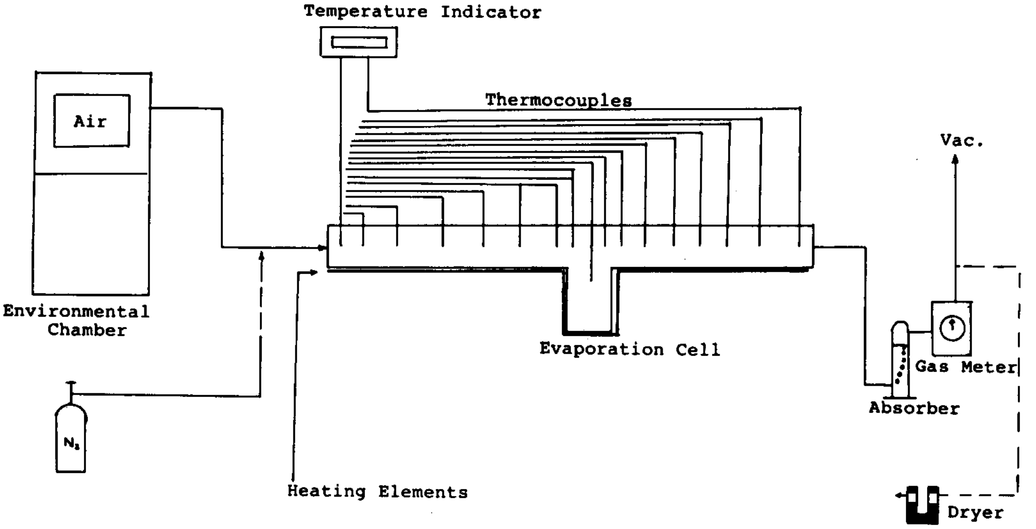

Fig. 6. Diagram of the apparatus used to determine the mass transfer rate for boric acid to a laminar air stream.

eliminate end effects from the section containing the mass transport cell. The duct was heated by a number of separate rubber-coated electrical resistance heaters. In addition, the duct and heaters were insulated with three inches of fibrous insulation. Copper–constantan thermocouples placed 30 cm apart along the duct aided in the maintenance of the desired operating conditions.

The mass transfer cell had dimensions 15.1 X 15.2 X 7.3 cm^3 and was filled with test material to the level of the bottom of the inlet and outlet ducts. The mass transfer cell was also heated with electrical resistance heaters. Flanges were used to connect the test cell to the square ducts with rubber gaskets between the flanges as seals. The mass transfer area of the cell was level with the bottom inside surface of the duct.

The governing equations and boundary conditions which describe the isothermal system may be derived by assuming constant physical properties and no chemical reactions. The diffusion term is for movement perpendicular to the surface of the insulation while air movement is parallel to the surface of the insulation. Figure 7 contains a diagram of the system and the coordinates that were used. With these assumptions, the governing equations for this system become:

$$V_y \frac{\partial C_A}{\partial y} = D_{AB} \frac{\partial^2 C_A}{\partial x^2} \tag{2}$$

$$\frac{\partial P}{\partial y} = \mu \frac{\partial^2 V_y}{\partial x^2} \tag{3}$$

with boundary conditions

$$y = 0 \qquad C_A = 0 \tag{4}$$

$$x = 0 \qquad C_A = C_{AS}, \quad V_y = 0 \tag{5}$$

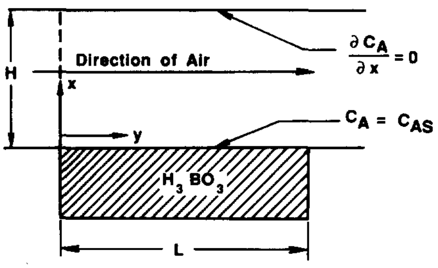

Fig. 7. Two-dimensional model for mass transfer of boric acid to flowing air.

$$x = H \qquad \frac{\partial C_A}{\partial x} = 0, \quad V_y = 0 \tag{6}$$

where

C_A = concentration of boric acid, g/cm^3;
C_{AS} = saturation concentration of boric acid, g/cm^3;
D_{AB} = diffusion coefficient of boric acid in air, cm^2/s;
H = height of square duct, cm;
V_y = air velocity in the y direction, cm/s;
μ = viscosity, g/cm s.

Equation (3) can be solved with the boundary conditions in eqns. (5) and (6) to give

$$V_y = 6V\left(\frac{x}{H} - \frac{x^2}{H^2}\right) \tag{7}$$

where V is the mean air velocity.

Substituting eqn. (6) into eqn. (1) gives

$$\frac{\partial^2 C_A}{\partial x^2} = \frac{6V}{D_{AB}}\left(\frac{x}{H} - \frac{x^2}{H^2}\right)\left(\frac{\partial C_A}{\partial y}\right) \tag{8}$$

Butler *et al.* [25] have applied the Leveque heat transfer equation for the laminar flow and derived a solution for eqn. (8). The solution for C_A was then used to calculate the mass transfer rate.

$$E = 1.45(LD_{AB})^{2/3}(\rho H^2 V)^{1/3}(P^s/P) \tag{9}$$

where

E = mass transfer rate, g/s;
L = length of the mass transfer cell, cm;
P^s = saturation vapor pressure, Pa;
P = total pressure of the system, Pa.

An alternate solution was obtained using an explicit finite difference method to solve eqns. (7) and (8). A comparison of results for the two solutions for water diffusing into nitrogen is shown in Table 4 and Fig. 8. The amount of material lost from the solid phase was obtained by summing across the vertical plane at $x = L$. As shown in Fig. 8, calculated results from eqn. (9) and the finite difference method show good agreement at low flow rates. The calculated results from eqn. (9) deviated from the experimental results at high flow rates. The finite difference method, therefore, was used to calculate the evaporation rate and estimate the diffusion coefficients for water into nitrogen or boric acid into air.

TABLE 4

Comparison of experimental and calculated evaporation rates for water into nitrogen at 28.4 °C

Nitrogen flow (cm^3/s)	Evaporation rate (g-mole/s × 10^{-5})				
	Expt.	Eqn. (12)	Finite diff.	Error (%)*	
				Eqn. (12)	Finite diff.
15.9	1.56	1.33	1.26	14.7	19.2
23.2	1.74	1.50	1.49	13.8	14.4
40.3	2.14	1.78	1.92	16.8	8.9
50.2	2.68	1.87	2.21	30.2	15.0

*% Error = (Exp — Calc) × 100/Exp.

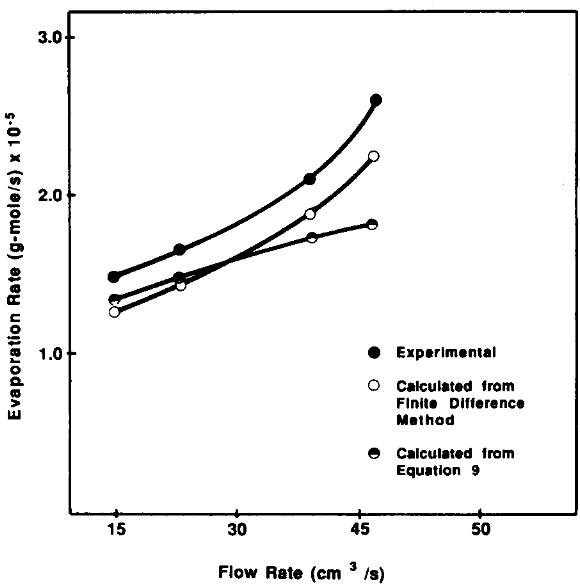

Fig. 8. Comparison of experimental and calculated evaporation rates for water into a flowing nitrogen stream at atmospheric pressure and 28.4 °C.

When applying this calculational method to the diffusion coefficient estimation, an objective function defined by eqn. (10) was used.

$$Se = |E_{\text{calc.}} - E_{\text{expt.}}| \tag{10}$$

An "optimum" diffusion coefficient resulted from minimization of *Se*. The experimental result for boric acid sublimed at 90 °C and 100% RH was 9.33×10^{-7} g/s. The resulting diffusion coefficient for boric acid in air was determined to be 0.114 cm^2/s at 90 °C.

LOSS OF BORIC ACID FROM CELLULOSIC INSULATION INSTALLED IN AN ATTIC

There are three important factors that influence the boric acid loss from cellulosic insulation installed on an attic floor; they are the temperature of the air in the attic, the humidity in the attic, and the air exchange rate. Calculations were performed for temperatures from 70 °C to 90 °C, relative humidities from 0% to 100% and air exchange rates from one to two attic volumes per hour for an attic with the following properties:

$V = 9.14 \times 9.14 \times 1.22$ m, attic volume of 101.91 m^3;
$A = 9.14 \times 9.14$ m, attic area of 83.54 m^2;
D = 15 cm, insulation thickness;
ρ = 43 kg/m^3, insulation density;
Y = 5%, initial amount of borax, weight percent;
X = initial amount of boric acid, weight percent.

Results are shown for initial boric acid contents of X = 15% and X = 20%. The value of 5 wt.% for the initial borax content was arbitrarily chosen to provide a starting point for the boric acid loss calculations. Calculations based on the information given above are shown in Fig. 9 along with the region identified by Day *et al.* [26] for the amount of borax and boric acid required to achieve smolder and flame retardancy. A move from the pass region to the fail region shown in Fig. 9 for X = 15% and X = 20% means losses of 13.5 kg and 40.4 kg of boric acid, respectively, from the cellulosic insulation. The time required to lose these amounts of boric acid at different temperatures, relative humidities, and air exchange rates were determined from the mathematical model.

If we assume that the attic described above represents a mass transfer cell with two large ducts connected to the cell, then the model developed for the apparatus will describe the

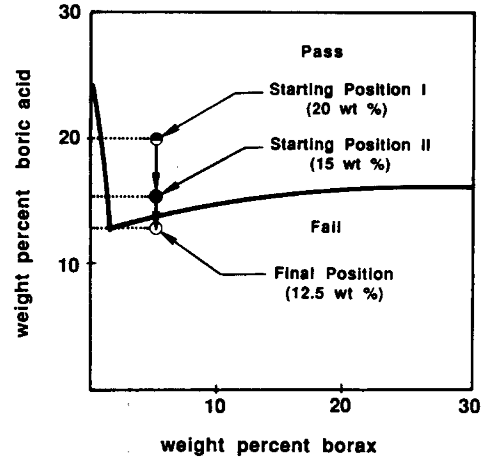

Fig. 9. Illustration of movement from passing region to failure region due to boric acid loss.

system, and the finite difference method can be used to calculate the mass transfer rate of boric acid from the insulation. The resistance to boric acid diffusion due to the solid fibers, however, needs to be introduced since the mass transfer from a pure boric acid particle bed will be greater than the mass transfer of boric acid distributed in cellulosic insulation. The mass transfer rate from the insulation was 62% of that from a particulate bed. The diffusion coefficient for boric acid in air was multiplied by 0.62 to account for the tortuosity of the insulation. From the assumptions and the calculational method outlined above, the results shown in Table 5 can be obtained.

It can be seen from Table 5 that increasing the initial weight percentage of boric acid from 15 wt% to 20 wt% will triple the time required to move from the pass region to the fail region. Figures 10 - 18 show calculated boric acid contents as a function of air exchange rate, temperature, relative humidity, and cumulative time at the specified conditions. Figures 10 - 14 each contain two sets of three lines; each set originates from an intercept representing the initial weight percent of boric acid contained in the insulation. The dashed curves in these Figures represent the boundary between the passing and failing regions shown in Fig. 9. The intersection of a solid line with the horizontal dashed line gives the predicted exposure time for the treated cellulosic insulation to cross the pass–fail line. Figures 15 - 18 present the calculated results in a different format. These Figures show the sensitivity of the loss rate to the system temperature or relative humidity. The 70 °C system is likely to be an upper bound on the temperatures occurring in residential attic spaces for even short periods of time. The calculated results are based on cumulative exposure of the attic insulation to stated temperatures, relative humidities, and air exchange rates.

TABLE 5

Calculated time required for loose-fill cellulosic insulation to move from pass to fail

T (°C)	RH (%)	Air exchange rate (attic vols. per hour)	Evaporation rate (g-mole/s)	Time (years)	
				15 wt%* chemical	20 wt%* chemical
90	100	1.0	1.050×10^{-3}	0.41	1.22
90	100	1.5	1.353×10^{-3}	0.31	0.94
90	100	2.0	1.621×10^{-3}	0.27	0.80
90	50	1.0	5.327×10^{-4}	0.80	2.41
90	50	1.5	6.820×10^{-4}	0.63	1.89
90	50	2.0	8.203×10^{-4}	0.52	1.56
90	1	1.0	1.077×10^{-5}	39.74	119.22
90	1	1.5	1.383×10^{-5}	30.95	92.85
90	1	2.0	1.659×10^{-5}	25.80	77.40
80	100	1.0	5.403×10^{-4}	0.80	2.59
80	100	1.5	6.938×10^{-4}	0.62	1.85
80	100	2.0	8.358×10^{-4}	0.51	1.54
70	100	1.0	8.240×10^{-7}	519.71	1559.20
70	100	1.5	1.062×10^{-6}	402.82	1208.45
70	100	2.0	1.272×10^{-6}	336.68	1010.05

*Starting weight percent of chemical in the insulation.

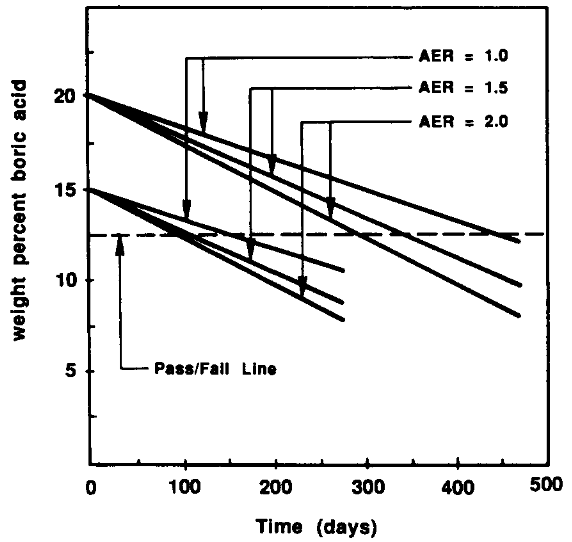

Fig. 10. Loss of boric acid from loose-fill cellulosic insulation at 90 °C and 100% relative humidity at various air exchange rates.

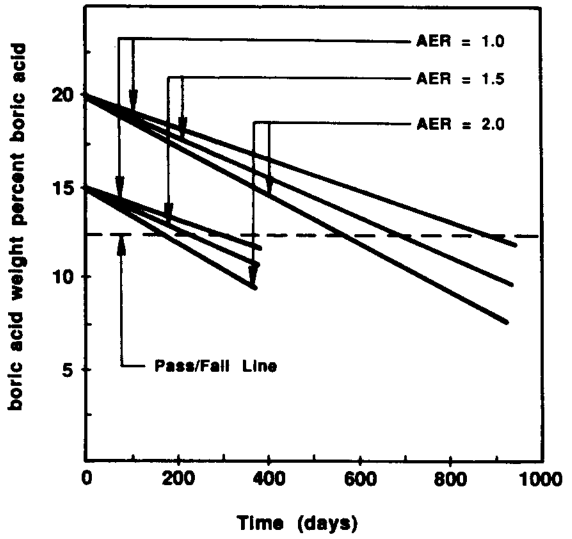

Fig. 11. Loss of boric acid from loose-fill cellulosic insulation at 90 °C and 50% relative humidity at various air exchange rates.

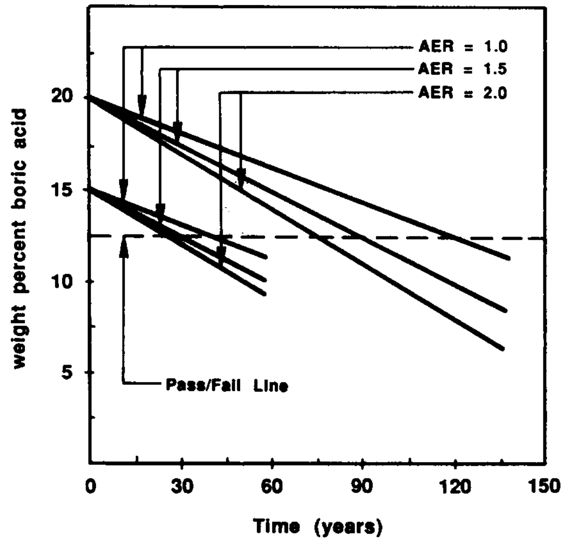

Fig. 12. Loss of boric acid from loose-fill cellulosic insulation at 90 °C and 1.0% relative humidity at various air exchange rates.

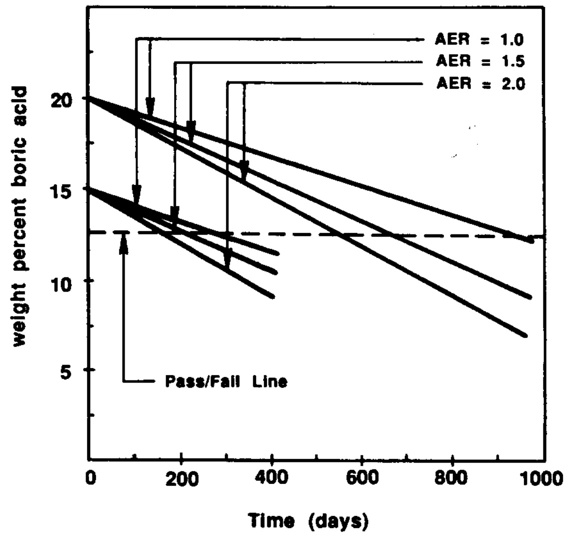

Fig. 13. Loss of boric acid from loose-fill cellulosic insulation at 80 °C and 100% relative humidity at various air exchange rates.

In the study of the influence of environment on the fire performance of loose-fill cellulosic insulation by the U.S. National Institute of Standards and Technology (NIST) previously known as the National Bureau of Standards (NBS) [9], a survey of weather conditions for eleven cities located in the United States was completed. Findings from this study were used to develop conditioning cycles to simulate the influence of temperature and humidity changes on the results of the smolder combustion and critical radiant flux testing required for cellulosic insulation. According to this study, the extreme climatic conditions were 35 °C, 90% relative humidity and 60 °C, 10% relative humidity. Table 5 shows that when the temperature is below 70 °C, the boric acid loss rate is very small.

CONCLUSIONS

A study of the loss of boric acid used as fire retardant in cellulosic insulation has been

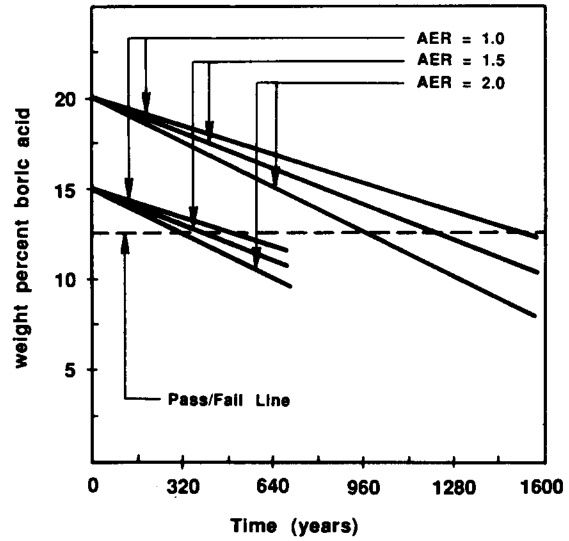

Fig. 14. Loss of boric acid from loose-fill cellulosic insulation at 70 °C and 100% relative humidity at various air exchange rates.

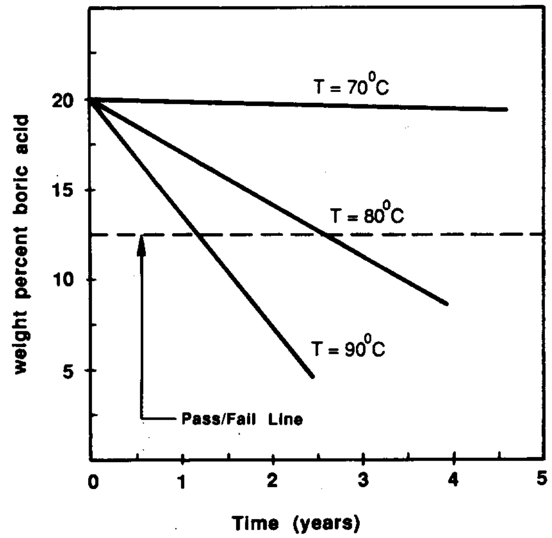

Fig. 15. Loss of boric acid from loose-fill cellulosic insulation at 100% relative humidity and air exchange rate of 1.0.

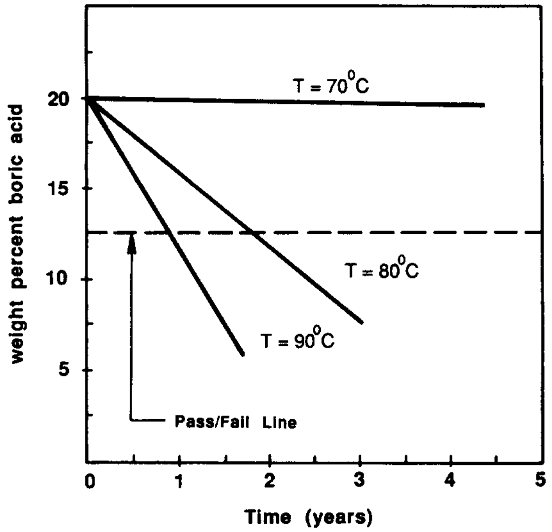

Fig. 16. Loss of boric acid from loose-fill cellulosic insulation at 100% relative humidity and air exchange rate of 2.0.

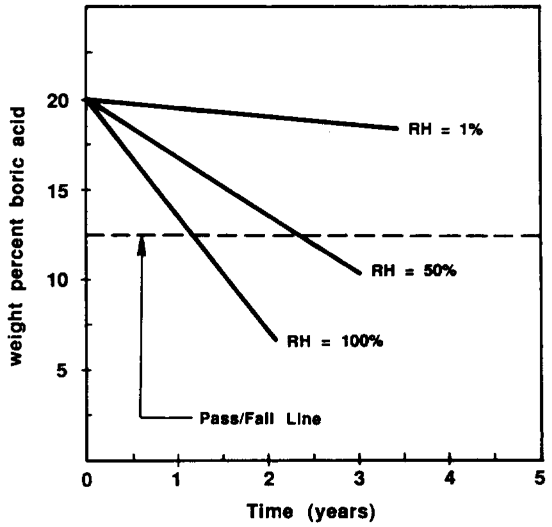

Fig. 17. Loss of boric acid from loose-fill cellulosic insulation at 90 °C and air exchange rate of 1.0 at various relative humidities.

reported for two loss mechanisms. The mass loss rate of boric acid from cellulosic insulation is negligible when the temperature is below 70 °C at any relative humidity and air exchange rates from 1.0 to 2.0 attic volumes per hour. It appears that it would take 300 years or more at 70 °C, 100% relative humidity, and air exchange rates from 1.0 to 2.0 attic volumes per hour to lose enough boric acid to significantly affect the combustion tests. Thus, it may be concluded that sublimation of boric acid from installed attic insulation is not an important loss mechanism.

The mechanical separation of boric acid and borax from cellulosic insulation due to 0.076 mm vibrations at 60 hertz for long periods of time was found to be negligible. It is concluded, therefore, that redistribution of boric acid or borax in attic insulation does not seem to be an important factor.

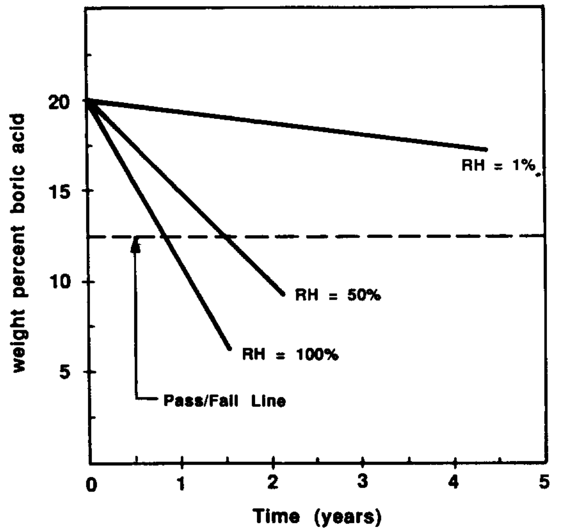

Fig. 18. Loss of boric acid from loose-fill cellulosic insulation at 90 °C and air exchange rate of 2.0 at various relative humidities.

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