

Heating System-Generated Indoor Air Pollution

SAMUEL SILBERSTEIN

Biomedical and Environmental Assessment Division, National Center for Analysis of Energy Systems, Brookhaven National Laboratory, Associated Universities, Inc., Upton, N.Y. 11973 (U.S.A.)

(Received October 31, 1978; in revised form May 31, 1979)

Heating systems may emit pollutants into living spaces of buildings. In this paper we try to answer the questions: 1) How can we estimate exposure to these pollutants? and 2) how will their concentrations be affected by energy conservation measures?

In order to answer the first question, we derived a differential equation and a simple APL program for numerical integration. This new model allows for variation during the day of v , the air exchange rate, and ΔT , the inside-outside temperature difference. This is necessary because heating systems operate and pollute most at night, when it is coldest outside, when v is greatest and when the greatest number of people is at home. Ignoring these variations could result in underestimating nighttime pollutant levels by as much as 1.5 - 2-fold.

The model also shows that ΔT and v may be assumed constant in order to answer the second question, as we have previously done. We conclude that if infiltration heat loss I , the proportion of heat lost by convection, is prevented from rising, then v may be reduced without increasing heating system-generated pollution. I may be kept constant by "balanced conservation" that is simultaneous reduction of v and installation of insulation.

INTRODUCTION

It is uncertain whether there is a serious problem of heating system emissions into living spaces of buildings. Obviously a faulty heater can contaminate air with CO, NO, NO₂, SO₂ and particulates, but there is little data on the prevalence of faulty heaters. It is unknown whether there are other explanations for pollutant release. A study of Biersteker *et al.* [1] of 60 homes heated by gas,

oil and coal indicated that newer homes have lower SO₂ levels and are less likely to have faulty heating systems than older ones. A recent Lawrence Berkeley Lab. study [2, 3] showed that a gas-fired forced air heater can raise NO₂ levels, but the mechanism was not determined.

In this paper we try to answer two questions: 1) How can we estimate exposure to heating system-generated air pollutants? and 2) how will their concentrations be affected by energy conservation measures?

In order to answer the first question, we derived a model that accounts for variation during the day of v , the air exchange rate, and ΔT , the inside-outside temperature difference, since no existing model adequately considered diurnal variations. It is necessary to do so because heating systems operate and pollute most at night when it is coldest outside, when v is greatest and when the greatest number of people is at home. As we will see, ignoring these variations could result in underestimating nighttime pollutant levels by as much as 1.5 - 2-fold.

Conservation measures that tighten building envelopes increase retention of indoor-generated pollutants. We previously found [4, 5] that because of increased retention, pollutant concentrations due to heating are raised when v is lowered in isolation, even though the decreased heat requirement allows a lower pollutant production rate by the heating system. In these estimates, we assumed steadystate levels resulting from heating system operation at a constant rate over a long period of time. These results are close to those obtained by applying the new model. Thus daily variation in v and ΔT may be neglected in estimating relative pollutant concentrations corresponding to different levels of conservation, but not in estimating

actual pollutant concentrations to which people are exposed at different times of the day.

Since v is rarely lowered in isolation, we also explore more realistic combinations of conservation measures and find that with "balanced conservation" (reduction in v together with addition of sufficient insulation) heating system pollution contributions need not rise.

THE MODEL

Our analysis assumes that ΔT , the temperature difference between indoors and outdoors, varies sinusoidally:

$$\Delta T = \overline{\Delta T} + \frac{1}{2} T_r \cos \theta \quad (1)$$

where $\overline{\Delta T}$ = average value of ΔT , T_r = daily temperature range, $\theta = (\pi/12 \text{ hr})(t - t_0)$, t = time of day and $t_0 = 12$ hours before or after ΔT achieves its maximum. The Achenbach-Coblentz model [6] assumes that:

$$v = v_0 + c|\Delta T| + c'w \quad (v_0, c \text{ and } c' \text{ are constants})$$

where w = wind speed; that is, v is linear in $|\Delta T|$ and w . Conceivably, v may also depend on $(\Delta T)^2$, on wind direction and on interactions between ΔT and w . If w is covariant with ΔT , no modification of our analysis is necessary. In general, though, wind speed and direction are not nearly as correlated with time of day as is ΔT and depend strongly on the particular locale. Although we do not explicitly take w into account, measurements of v yield a value that is an average for various wind conditions, and unless the wind is very strong, our conclusions should still hold. Thus we assume:

$$v = v_0 + c|\Delta T| \quad (2)$$

We choose t_0 in this way in order to get a pollution peak near $t - t_0 = 12$ h, the center of our graphs. $t = t_0 + 12$ h occurs in the late night or early morning, a time we are most interested in. If minimum ΔT does not occur exactly at t_0 , our results should not be greatly affected.

As previously [4] we assume that indoor and outdoor air are uniform and that the rate of pollutant production is directly proportional to the rate of heating system operation,

which, if ΔT is small enough, varies linearly with v :

$$\text{pollutant production rate} = (a + bv)\Delta T k_h \quad (3)$$

(a and b are constants described in [4])

where k_h = production rate of pollutant per unit building volume by continuous heating. The rate of pollutant removal is given by

$$\text{pollutant removal rate} = v(p - p_0) \quad (4)$$

where p = indoor concentration of any pollutant, P , produced by heating and p_0 = its outdoor concentration. We assume p_0 constant. We are most interested in the value of p at night when p_0 is likely to be small. In the Appendix we solve the differential equation

$$p' = dp/dt = \text{pollutant production rate} - \text{pollutant removal rate.}$$

In our analysis we assume

$$\overline{\Delta T} = 20^\circ\text{C}$$

$$T_r = 10^\circ\text{C}$$

$$a = \frac{1}{80^\circ\text{C}}$$

and

$$b = \text{either } 1 \text{ h or } \frac{1}{4} \text{ h.}$$

Note that, from eqns. (1) and (2)

$$v_{\min} = v_0 + c(\Delta T)_{\min} = v_0 + c \times 15^\circ\text{C} \quad (6)$$

$$\bar{v} = v_{\text{avg}} = v_0 + c\overline{\Delta T} = v_0 + c \times 20^\circ\text{C}$$

$$v_{\max} = v_0 + c(\Delta T)_{\max} = v_0 + c \times 25^\circ\text{C}$$

If we fix v_{\min} , \bar{v} and v_{\max} , then c and v_0 are determined. For example, if $\bar{v} = \frac{3}{4}$ air change per hour (ach) and $v_{\max} = 1.4v_{\min}$, then

$$c = 0.025 \frac{\text{ach}}{^\circ\text{C}} \text{ and } v_0 = \frac{1}{4} \text{ ach.}$$

In the next section we present the results of our analysis for what we feel are realistically chosen v_{\min} , \bar{v} and v_{\max} .

RESULTS

Effects of diurnal variation in v

Figure 1 is a pollutant production profile for $\bar{v} = \frac{3}{4}$ ach and $v_{\max} = 1.4 v_{\min}$. Heating system pollutant production peaks at $t - t_0 = 12$ h as it was meant to. Figure 2 illus-

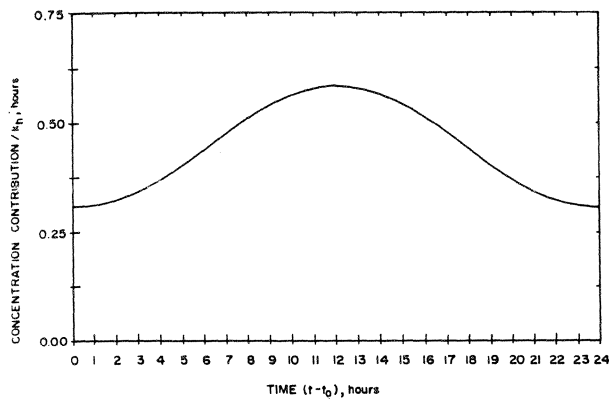


Fig. 1. Typical heating system pollutant production rate (normalized). $\bar{v} = \frac{3}{4}$ ach, $c = 0.025$ ach/°C, $b = a$ h.

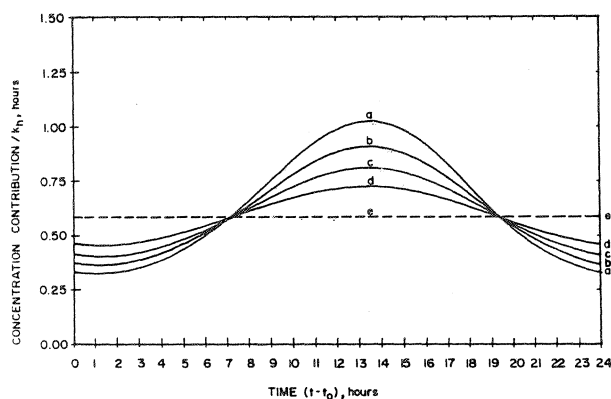


Fig. 2. Effect of diurnal variation in v on pollutant concentration contributed by heating system (normalized). $v = \frac{3}{4}$ ach, $c = 0.025$ ach/°C, $b = a$ h.

	c (ach/°C)
(a)	0.0375
(b)	0.0250
(c)	0.0125
(d) constant v case	0
(e) constant case	0 (ΔT is constant also)

trates the effects on p of varying c while maintaining \bar{v} at $\frac{3}{4}$ ach. Also shown is the steady-state solution [4], $p_s = (a/\bar{v} + b)\Delta T k_h$. (We shall call the latter the "constant case" and the case when $c = 0$ but ΔT is permitted to vary, the "constant v case".) While the average daily pollutant concentration \bar{p} is identical for the constant and the constant v cases, the constant v case has a higher pollutant concentration at night, when more

people can be expected to be at home. We estimate the average heating system contribution to pollutant concentration at night to be $\bar{p} + \sigma$ ($\sigma =$ the variance of p about \bar{p}), as in [7]. The nightly average contribution for the constant v case is 17% higher than for the constant case, and the maximum 23% higher (Table 1).

We vary c from 0 to 0.0375 ach/°C. The latter value corresponds to $v_0 = 0$ ach, an extreme case*. As c increases, not only does the daily average p increase, but the nightly average and maximum increase by much larger amounts (Table 1). For example, for $c = 0.025$ ach/°C, corresponding to a fluctuation in v of 40% from its minimum to its maximum, the daily average pollution is only 5% higher than for both the constant and constant v cases, but the nightly average is 19% higher than the nightly average for the constant v case and 39% higher than p for the constant case. The discrepancy in the maxima is even greater: 26% higher than for the constant v case and 55% higher than p for the constant case. A fluctuation of 40% from v_{\min} to v_{\max} is close to a result obtained for an actual building in the temperature range we are considering [8].

Note that the maximum pollutant concentration lags behind the maximum production rate by almost 2 h, independently of c . The lag is as expected from [7] because when $c = 0$,

$$p = \bar{p} + C_1 \cos \theta + C_2 \sin \theta \quad (7)$$

(C_1 and C_2 are constants given in the Appendix)

and when p has this form [7] predicts a lag time that varies in an inverse manner with v^{**} .

Effects of lowering \bar{v}

We will show that if infiltrative heat loss is kept constant, then pollutant contributions from heating equipment need not rise when v

*Actually it is conceivable that $v_0 = 0$ ach can be obtained in practice. For example, in our case ΔT varies from 15 - 25 °C and a linear relationship is assumed between v and ΔT in this range. By extrapolating ΔT to 0 °C we obtain v_0 . However, v_0 may not actually correspond to the actual value of v when $\Delta T = 0$ °C because there may be a different linear relationship between v and ΔT near $\Delta T = 0$ °C.

**See also Fig. 3 for further confirmation.

TABLE 1

Effects of varying v on $p - p_0$ when $\bar{v} = 3/4$ ach

v_{\max} v_{\min}	c (ach/ $^{\circ}$ C)	v_0 (ach)	% Increase of average over either cvc^a or cc^b	% Increase of nightly average over cvc^a over cc^b		% Increase of maximum over cvc^a over cc^b	
1.00	0.0	3/4	0.0	0.0	16.7	0.0	23.4
1.18	0.0125	1/2	1.8	8.9	27.1	11.9	38.2
1.40	0.025	1/4	4.6	18.7	38.6	25.6	55.0
1.67	0.375	0.0	8.4	30.3	52.1	41.9	75.1

^a cvc = constant v case.^b cc = constant case.

is reduced. Assume v and ΔT constant. Infiltrative heat loss I is the proportion of heat lost via convection:

$$I = \frac{bv}{a + bv} \quad (8)$$

Recall that $p_s = \{(a + bv)/v\} \Delta T k_h$ when v is constant. Therefore

$$p_s = \frac{b}{I} \Delta T k_h \quad (9)$$

This shows that p_s varies inversely with I ; if I is kept constant then so is p_s . We make a few observations about this result:

1) It requires linearity between heat loss and v ; b must be constant over the entire range over which v is reduced. While this undoubtedly occurs for a small reduction in v , deviations from linearity may occur for a large reduction. For example, heat loss may be proportional to $ae^{bv/a}$ instead of to $a + bv$.

2) The ratio bv/a is a measure of the relative efficacy in conservation of reducing convective vs. conductive and radiative heat loss; bv/a is estimated to be about $1/2$ (equivalently $I \approx 1/3$) for townhouses in Twin Rivers, N.J. [9]. If bv/a (or I) is kept constant while v is reduced, then p_s (due to heating system emissions only) will also remain constant. This requires that convective and non-convective heat loss be reduced in the same proportion. Indeed, if non-convective heat loss is reduced relatively more than convective heat loss (for example, by extensive insulation) then heating system-generated indoor air pollution may actually be reduced even though v is lowered. For example, we calculate that for a town house in Twin Rivers for which a 68% reduction in energy use was achieved [10], heating system-generated pollution (if any)

was reduced 15% even though v was reduced 62%!

3) We have assumed that heating system emissions vary with the proportion of time that the heating system operates (eqn. (3)). This relationship probably does not hold when the proportion of time is very small because frequent switching on and off probably results in inefficient combustion, and thus higher emission rates than predicted.

4) If heating system efficiency remained constant for all modes of operation, then as long as I was kept constant there would be sufficient make-up air for combustion since the proportion of air entering the building by infiltration needed for combustion would remain constant*. However, increasing heating system inefficiency resulting from frequent cycling on and off might cause stuffiness due to failure to adequately replace combustion air with fresh air. (Inefficient combustion would remove more O_2 than could be replaced, slightly lowering air pressure and permitting greater leakage or backing-up of pollutants from the furnace.)

In Fig. 3 we illustrate reduction in \bar{v} (v is no longer assumed constant) in isolation, that is, in the absence of insulation. Curves (c) and (d) are heating system-generated pollution profiles for $\bar{v} = 1.4$ ach, $v_{\max} = 1.15 v_{\min}$ and $b = a$ h and $1/4 a$ h, corresponding to $I = 0.58$ and 0.26 , respectively. (I is calculated using \bar{v} ; this is much easier than calculating the average daily value of I and the results are nearly identical (not shown).) The absolute

*This follows from: (proportion of fresh air needed for combustion = $(1/v \times \text{rate of } O_2 \text{ consumption})$ proportional to $(1/v \times \text{proportion of time heating system operates})$ proportional to $(a + bv)/v = b/I$. If I is constant, then so is the first term.

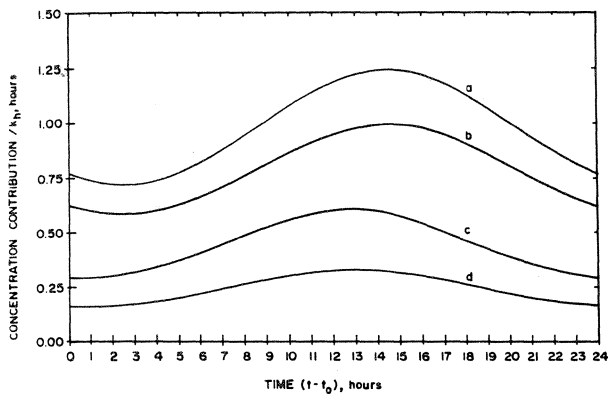


Fig. 3. Effect of \bar{v} on pollutant concentration contributed by heating system (normalized). $c = \bar{v}/70^\circ\text{C}$.

	\bar{v} (ach)	I	b/a (h)
(a)	0.35	0.26	1
(b)	0.35	0.08	1/4
(c)	1.4	0.58	1
(d)	1.4	0.26	1/4

sizes of a and b are unimportant as long as they are small enough for the heating system to be capable of maintaining the same inside temperature over the entire range of v and ΔT . That is

$$(a + bv_{\max})(\Delta T)_{\max} \leq 1 \quad (10)$$

((ΔT)_{max} = 25 °C here)

(When $\Delta T = 20^\circ\text{C}$ then $T_{\text{in}} \approx 20^\circ\text{C}$, $\bar{T}_{\text{out}} \approx 0^\circ\text{C}$ and $(T_{\text{out}})_{\text{min}} \approx -5^\circ\text{C}$. At these temperatures, it is realistic to assume that a heating system need not operate at capacity.)

If \bar{v} is reduced 4-fold to 0.35 ach, then pollutant profile (c) becomes (a) and (d) becomes (b). The range for I declines to 0.08 - 0.26, a low range that reflects the unrealistic practice of reducing \bar{v} in isolation. Actual buildings are estimated to have I in the range 0.1 - 0.5 [13]. Thus in Fig. 3 I is reduced from the upper half of this range to the lower half.

Table 2 shows the increase in p_{\max} , \bar{p} and the nightly average of p for the 2 values of b when \bar{v} is lowered 4-fold from 1.4 to 0.35 ach. We compare these increases to the increase in p_s if v and ΔT are assumed constant at their average values, and find that for each value of b the increases are similar; all

these pollution measures roughly double for $b = a$ h and triple for $b = 1/4a$ h. We can conclude that in order to accurately estimate heating system-generated indoor air pollution levels it is necessary to take daily variation of v and ΔT into account, but to merely compare relative pollutant levels for different \bar{v} , v and ΔT can be assumed constant, as in [4].

Furthermore, suppose p_i are heating system-generated indoor air pollution profiles corresponding to I_i ($i = 1, 2$) with $p_{s,i}$, \bar{p}_i and $p_{\max,i}$ defined similarly. Since

$$\frac{p_{s,1}}{p_{s,2}} = \frac{I_2}{I_1} \quad (11)$$

(from eqn. (9)) and p_s , \bar{p} , nightly average p and p_{\max} all vary in the same way with v (Table II), any of these pollution measures can be substituted for p_s in eqn. (11); for example

$$\frac{\bar{p}_1}{\bar{p}_2} = \frac{p_{\max,1}}{p_{\max,2}} = \frac{I_2}{I_1} \quad (11')$$

CONCLUSIONS AND DISCUSSION

Heating system-generated air pollution may contribute significantly to indoor air quality deterioration. We developed a new model since there are no adequate existing models for estimating exposure to heating system pollution.

Not only is heating system-generated indoor air pollution greatest at night when heating system operation is at a maximum to compensate for the high values of ΔT and v that occur at that time but more people are at home at night than during the day and thus exposed to these higher levels. The model allows for variation in v and ΔT and permits estimation of actual exposure levels from knowledge of building and heating system characteristics and pollution measurements taken at any time of the day. Ignoring these variations could result in underestimating nighttime pollution levels by as much as 1.5 - 2-fold.

Pollutant concentrations for different levels of energy conservation, however, can be adequately compared by assuming v and ΔT constant, whether p_s , \bar{p} , nightly average p or p_{\max} are used as pollution measures. We

TABLE 2
Effects of varying \bar{v} on $p - p_0$ for 2 values of b

	$b = a h$		$b = \frac{1}{4} a h$	
	$\Delta T, v$ vary	$\Delta T, v$ constant at their average values	$\Delta T, v$ vary	$\Delta T, v$ constant at their average values
avg ($\bar{v} = 0.35$ ach)	2.24		3.20	
avg ($\bar{v} = 1.4$ ach)				
nightly avg ($\bar{v} = 0.35$ ach)	2.10	2.25	3.07	3.22
nightly avg ($\bar{v} = 1.4$ ach)				
max ($\bar{v} = 0.35$ ach)	2.07		2.99	
max ($\bar{v} = 1.4$ ach)				

confirmed our previous result [4] that reducing v 4-fold in isolation could raise heating system pollutant contributions up to 3-fold. However, if conservation measures are carried out in a "balanced" manner, that is, non-convective heat loss is reduced in the same proportion as convective heat loss, then pollutant contributions will remain unchanged. Thus, aggravation of heating system-generated indoor air pollution by energy conservation can be avoided by adding sufficient amounts of insulation. It may be possible to have very tight building envelopes ($v < \frac{1}{4} - \frac{1}{2}$ ach) without having to eliminate gas or oil-fired furnaces as long as there is adequate replacement of combustion air with fresh air. Inadequate replacement could result from frequent cycling on and off by the furnace, an inefficient mode of operation that raises the proportion of fresh air needed for combustion. Possible solutions to this problem are the use of a smaller furnace or of outside air for combustion.

This analysis applies only to heating system-generated pollution. Retention of pollutants from other sources such as cigarette smoke will increase in response to lowering v , causing significant air quality deterioration [4, 5]. This problem may be more intractable than heating system pollution.

APPENDIX

In this section we solve eqn. (5):

$$p' = (a + bv)\Delta T k_h - v(p - p_0) \quad (5)$$

Substituting eqns. (1) and (2) for ΔT and v , respectively, we obtain:

$$p' = \alpha - \beta \cos \theta + \gamma \cos^2 \theta - (\delta + \epsilon \cos \theta)(p - p_0) \quad (12)$$

where

$$\frac{\alpha}{k_h} = (a + bv_0)\overline{\Delta T} + bc\overline{\Delta T}^2 \quad (13)$$

$$\frac{\beta}{k_h} = bcT_r\overline{\Delta T} + \frac{1}{2}(a + bv_0)T_r$$

$$\frac{\gamma}{k_h} = \frac{1}{4}bcT_r^2$$

$$\delta = \bar{v} = v_0 + c\overline{\Delta T}$$

and

$$\epsilon = \frac{1}{2}cT_r$$

If $c = 0$, then

$$\frac{\alpha}{k_h} = (a + bv_0)\overline{\Delta T} \quad (13)$$

$$\frac{\beta}{k_h} = \frac{1}{2}(a + bv_0)T_r$$

$$\gamma = 0$$

$$\delta = v_0$$

$$\epsilon = 0$$

In this case eqn. (12) reduces to

$$p' = \alpha - \beta \cos \theta - v_0(p - p_0) \quad (12')$$

which can be solved either by integrating

analytically eqn. (13) below or by the techniques of [7] to obtain eqn. (7) with

$$\bar{p} = p_0 + \frac{\alpha}{v_0} \quad (7')$$

$$C_1 = - \frac{\beta v_0}{(\theta')^2 + v_0^2}$$

and

$$C_2 = - \frac{\beta \theta'}{(\theta')^2 + v_0^2}$$

Now for a differential equation of the form

$$f' + fq = r \quad (14)$$

the general solution is given by the sum of the general solution of the homogeneous equation corresponding to eqn. (14) ($f' + fq = 0$) and any particular solution of eqn. (14). A general solution of the homogeneous solution corresponding to eqn. (14) is given by

$$f = K \exp \left\{ -\delta t - \frac{\epsilon}{\theta'} \sin \theta \right\}$$

where K is an integration constant. We insist that f be periodic; this is impossible when $\delta \neq 0$ unless $K = 0$, that is, the only periodic solution of p when there is no internal pollution production is

$$p = p_0$$

A particular solution for eqn. (14) is given by

$$f = e^{-fr} \int q e^{fr} \quad (15)$$

with constant of integration to be determined later.

This translates into

$$p - p_0 = \exp \left\{ -\delta t - \frac{12 \text{ hr}}{\pi} \epsilon \sin \theta \right\} \times \\ \times \left\{ (\alpha - \beta \cos \theta + \gamma \cos^2 \theta) \exp \left\{ \delta t + \frac{12 \text{ hr}}{\pi} \epsilon \sin \theta \right\} \right\} dt \quad (16)$$

The expression under the integral in eqn. (16) must be solved numerically unless $c = 0$. We have designed a simple APL computer program that numerically integrates continuous functions on closed, finite intervals. The

program randomly samples 100 points in the interval of integration, evaluates the function at those points, averages these function values and multiplies by the length of the interval. This process is repeated 10 times and the 10 values are averaged to obtain the integral*. The program is given in Fig. 4.

```
[0] S ← X1 INT X2
[1] I ← 0
[2] INTF ← f0
[3] L1: I ← I + 1
[4] W ← 100? 1000000000
[5] Y ← X1 + (X2-X1) × W ÷ 1000000000
[6] INTF ← INTF, ((+/FCN Y) ÷ 100)
[7] → (I < 10) / L1
[8] S ← (+/INTF) × (X2-X1) ÷ 10

[0] F ← FCN U
[1] F ← (AL + (GA × (2o(oU ÷ 12)) * 2) - (BE ×
      2o(oU ÷ 12))) × ((DE × U) + (EP ×
      1o(oU ÷ 12)) × 12 ÷ o1)
```

Fig. 4. APL program (INT) for the integral of a continuous function on the interval (X_1 , X_2) followed by the actual function (FCN) used in the text (eqn. (12)).

We give the program used to obtain the solution to eqn. (12) in Fig. 5. The program was run twice on an IBM 5100 minicomputer. In the first run the initial value (INIT) or $p - p_0$ in eqn. (16) was set at 0; in the second to the final value of the previous run in order to obtain a periodic solution**. This program does not yield identical values for the integral on each run, but a maximum difference between initial and final values of a periodic function of no more than 1.3% in each of 8 runs indicates the reproducibility of the integration.

For purposes of computing means and variances, the values for 0 and 24 hours were averaged and considered to be 1 point, resulting in 24 points in all.

*This may be done 100 times for greater accuracy. This method is much faster than sampling 1,000 or 10,000 points in the interval only once.

**INIT determines the integration constants for each interval as well, as can be seen by examination of Fig. 5.