Studying Air Exchange in Premises
using Radioactive Tracers

Translated from the original Russian
"Izuchenie vozdukhooobmena v pomeshcheniyakh metodom radio-aktivnykh indikatorov"
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Translator: Dr L Queen
Translator's note.

There are several abbreviations whose meaning I do not know. In these cases, I have chosen what seems the most appropriate transliteration. Here is a complete list, with Russian originals:

ΛИСИ  LISI (Leningrad Institute of Building Industry?)
ΠАК  PDC
ΣΤΣ-5  ΣΤΣ-5, etc
ΒΕΣΜ-6  BESM-6
ΚΜΤ-14  ΚΜΤ-14
Η-115  N-115
Η-700  N-700
Φ-588  F-588
ΠΓ2/1-2  PG2/1-2 etc
ΥΓ-2  UG-2
ΠΟΥ-2  POU-2
ΟΒ-5  OV-5
ΑΣΟ-3  ACO-3
ΤΑ-8  TA-8

Ки/м³  KI/m³  a unit of intensity
Па  Pa  a unit of pressure.

Names of technical equipment
Studying Air Exchange in Premises using Radioactive Tracers.

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To create comfortable conditions and to estimate the efficiency of insulation materials, we require data on the air regime of the premises. Special attention should be paid to integral air exchange, which is one of the most important characteristics of the air regime.

Air exchange can be estimated by measuring the air velocity in ventilation openings. This is not an accurate method: it is impossible to characterise the mixing of inflowing and internal air, to locate stationary zones, it is hard to measure the natural air exchange, the anemometer at the channel entrance determines air velocity only with a large error; and it is complicated to study non-stationary processes, such as ventilation of means of transport while in motion. There are also disadvantages in detecting air exchange by measuring the heat output of heating devices $Q_1$, and subtracting from them the heat losses of transmission $Q_2$. The air exchange can be found only with an error of about 100% since $Q_1$ and $Q_2$ are close in magnitude.
The tracer gas method is more accurate [1]. An increased concentration of a certain gas is created in the premises, and the air exchange is found by its decrease. However, because of the choice of samples and the small sensitivity of gas-analysers, the measurements take a long time and are uneconomic. Mixture concentrations are required that are much higher than PDC; and continuous recording of data using chemical tracers is difficult.

The possibilities of tracer gases are extended by radioisotopes. Their advantage lies in a considerably higher sensitivity to mixtures (Fig. 1). Hence, without losing accuracy, the experiment can be performed using a considerably smaller tracer concentration than in other cases.

The more sensitive a technique is, the stronger is the signal of a recording device caused by a given concentration. With a strong signal, the relative errors are smaller. Hence, the more sensitive a technique is, the more accurate it is. The connection between the signal of a device N, the sensitivity S and the mixture concentration q is described by the formula, which follows from [2]:

$$\varepsilon_q = \frac{N}{qS} \left( \sum_{i=1}^{k} \varepsilon_i \right)^{1/2}$$

where $\varepsilon_q$ and $\varepsilon_i$ are the mean square relative errors in measuring q and N ($\varepsilon$ takes into account the effect of various factors on N); the sensitivity is introduced as the ratio of the change of signal dN to the change of the mixture concentration dq which has caused it.
Because of its high sensitivity, the accuracy of the radioisotope technique is greater than that of the usual methods, even when the latter are performed under optimal conditions. This was demonstrated by the experiments [3]. At the same time, as can be seen from formula (10), the accuracy of air exchange measurements depends on the accuracy of the measurements of tracer concentration.

The radioisotope technique is fast. By varying the activity of the mixture, the geometry, and the accuracy of the measurements, the time of a single determination of concentration can be reduced to one or two minutes. For this purpose the nomogram [4] is used. Comparison shows that the average time for a single concentration measurement by the heat-conductivity technique is 6 minutes, by the linear-technique 8 minutes, and by the colorimetry technique 15 minutes. The radioisotope technique also has the advantage of not taking air samples and analysing them, as well as the simplicity of automatic recording, which is particularly important in the study of non-stationary phenomena; for this we recommend the registering device developed in LII.

There have been a number of papers on the study of air exchange by the radioisotope technique abroad [5-8]. Even though they are undoubtedly interesting, they have certain limitations. They provide no substantiated data on air volume, or what is the source of information on air exchange, or the effect of the determining factors on the signal of the detector. Also, it is impossible to find in advance the mass of tracer to be injected into the premises in order to measure the air exchange with minimal activity.
These problems have been solved in LISI, where isotopes are used to model ventilation, to control local extractions, to study ventilation currents and air exchange in premises, and to forecast atmospheric contamination of the plant areas by industrial waste.

The method assumes a constant air flow through the test volume, and a uniform dispersion of the tracer:

\[ \frac{dL}{dt} = 0 \quad \text{and} \quad \frac{dq}{dr} = 0, \quad (2) \]

where \( L \) is the air exchange and \( r \) a space coordinate.

Under the conditions (2) the signal \( N \) of the receiver, proportional to the tracer concentration \( q \) at the instant \( t \), decreases according to the rule:

\[ N = N_0 \exp(-\mu t), \quad (3) \]

where \( N_0 \) is the signal proportional to the initial concentration \( q_0 \), and \( \mu \) is the multiplier for air exchange in the vicinity of the detector.

By a regression analysis [9], one finds the value of \( \mu \):

\[ \mu = \frac{\sum_{i=1}^{n} [(\tau_n - \tau_i) - T\ln N_i - C]}{\sum_{i=1}^{n} [(\tau_n - \tau_i) - T]^2}, \quad (4) \]

where \( N_i \) is the signal at time \( \tau_i \); \( n \) is the number of test points, and

\[ T = \frac{1}{n} \sum_{i=1}^{n} (\tau_n - \tau_i), \quad C = \frac{1}{n} \sum_{i=1}^{n} \ln N_i. \]

The dispersion of \( \mu \) is found by the formula:

\[ \sigma^2 = \frac{n \sum_{i=1}^{n} d_i^2}{(n-2) \sum_{i=1}^{n} [(\tau_n - \tau_i) - T]^2}, \quad (5) \]

where \( d_i = \ln N_i - C + [T - (\tau_n - \tau_i)]. \)
In [4] it is shown that Kr$^{85}$ and Xe$^{133}$, which are not absorbed by surfaces, are optimal. The receiver should give information on air exchange from a large volume, and so Kr$^{85}$ is preferable, since the maximal energy of its β-particles is almost twice as great as that of Xe$^{133}$. The output of γ-quanta for Kr$^{85}$ decay is small (0.4 %), dispensing with special shielding. Suitable receivers are cylindrical gas-discharge counters CTC-5 and CTC-6 and toral counters CBT-7 and CBT-9.

Calculations on the computer DESM-6 showed [10],[11] that β-particles from Kr$^{85}$ reach a cylindrical counter from a cylindrical volume of radius $R \approx 90$ cm and height from 1.3 to 1.4 times that of the counter. They reach a toral counter from the adjacent hemi-spherical volume of radius $R_0 \approx 1.2$m. Taking into account the curves given in Fig. 3, in order to exclude boundary effects the counter should be placed at a distance of not less than 80-90 cm from any barriers.

When planning an experiment, one should establish the relation between the error in measurement of μ and the determining factors. The formula for the mean square error $\varepsilon_\mu$, with accuracy up to terms of second order of smallness, can be deduced from expression (3) after considering small changes in the arguments, and passing over to finite increments. Since the relative errors in measurements of $N_0$ and $N$, while differing little from each other, are considerably larger than the relative error in measuring $\tau_n$, we have

$$\varepsilon_\mu = \frac{1.4 \varepsilon_N}{\mu \tau_n},$$

(10)

where $\varepsilon_N$ is the mean square error in measuring $N$. 

The errors in gas-radiometry are uncorrelated, and hence

$$\varepsilon N = (\varepsilon_C^2 + \varepsilon_M^2 + \varepsilon_a^2)^{1/2},$$

(11)

where $\varepsilon_C$, $\varepsilon_M$, and $\varepsilon_a$ are the statistical, methodical, and equipment-determined errors in measuring $N$.

The error $\varepsilon_C$ is caused by the fact that $\text{Kr}^{85}$ does not decay uniformly, and is controlled by the activity and the time of the measurement of its concentration. The error $\varepsilon_M$ is, on the whole, due to the non-uniform distribution of $\text{Kr}^{85}$ around the counter. It is not crucial - measures can be taken to mix the tracer. Finally, $\varepsilon_a$ is due to non-stability of the equipment. Devices for measuring air exchange are imprecise; as was shown by experiments of the authors using Pearson's $\chi^2$-criterion, the role of $\varepsilon_a$ can be ignored. Calculations show that at the last test point, according to $\mu \tau_n$, $\varepsilon_M = (0.3-0.7)\varepsilon_C$.

To ensure the required accuracy of measurements, the initial content of $\text{Kr}^{85}$ in the premises should be large. At the same time, however, it should be kept small so as to avoid tracer loss and exposing the staff. The equations mentioned above make it possible to find suitable experimental conditions. The experiment should be planned by taking the maximal error $\varepsilon$ which remains the same with reliability 95%, say, and exceeds $\varepsilon_{\mu}$ twice. If one takes into account the results of [4], then assuming conservatively that $\varepsilon_M \propto \varepsilon_C$ and using formulae (3), (10), (11), we obtain

$$q_o = \frac{16 \exp(\lambda \tau_n)}{S \mu^2 \tau_n^2 t \varepsilon_o^2},$$

(12)

where $\tau_n$ is the duration of the experiment; $t$ is the time to measure $N$; $S = N_o/q_o$. 

The sensitivity values $S$ for typical counters are given in [10] and [11]. In the same references are found the dependence of $S$ on the radius and height of the counter, thickness of its walls, maximal energies of the $\beta$-spectrum, etc.

Calculations show that a value of $q_o$ of the order of the average admissible value $(5 \cdot 9 \cdot 10^{-5} - 1 \cdot 4 \cdot 10^{-4})$ $\text{Ki/m}^3$ is sufficient. The staff can remain on the premises, since the possible doses fall within the limits of the natural background. The tests are preceded by an analogous preliminary experiment of 5-6 minutes duration, whose purpose is to estimate the value of $\mu$.

The activity $A$ which should be introduced into the premises is found by multiplying $q_o$ by the cubic capacity $V$. For practical purposes we recommend a nomogram (Fig. 4). It is constructed for $S = 45 \cdot 3$ imp.cm$^3$/decay, i.e., less than the computed 10 by 30\% (allowance for a possible increase in the wall of the counter by 15\% relative to the average one).

Example. To compute the activity of $\text{Kr}^{85}$ which should be injected into premises of volume 60$m^3$ in order to measure air exchange with an accuracy of up to 8\% for an experiment of duration 15 min. The signal at the last point is taken at 1 min. The tentative value of $\mu$ is 3.5 1/hr.

Solution. From the nomogram $q_o = 77 \cdot 10^{-5}$ $\text{Ki/m}^3$, whence $A = 4 \cdot 6$ mKi.

The equipment in Fig. 5 was developed to carry out the experiments. An ampoule with $\text{Kr}^{85}$ is placed into chamber 1 (Fig. 5a). On opening a tap of the cylinder 2, carrier gas pushes out the piston 3, which breaks the ampoule. The mixture is forced into cylinder 4 (from an inhaler $\text{KI-3M}$), increasing the pressure up to $3 \cdot 10^6 - 10^7$ Pa. After
charging, the mixer is disconnected and joined to the distributing system of hoses. Using these, the premises are injected with a volume of gas $V_M$, producing a given concentration:

$$V_M = \frac{q_oVN_CP_C}{A_CP_a} \quad (13)$$

where $V_C$ is the mixer volume; $A_C$ and $p_C$ are the activity of the tracer gas and the absolute pressure in the mixer; $p_a$ is atmospheric pressure.

If $A_C$ is unknown then one first finds the concentration of $Kr^{85}$ in the mixer. A sample of volume $V_P$ with concentration $q_C$ is taken from the mixer and placed into a chamber of volume $V_K$ with a counter. By measuring the signal $M_K$ from the tracer gas in the chamber, and knowing $S$, one determines $V_M$:

$$V_M = \frac{q_oVN_PS}{N_K} \quad (14)$$

When $Kr^{85}$ was introduced into premises using the distributing system, $V_M$ was controlled by a flow-measuring device based on thermoresistors KMT-14. For small premises $V_M$ was taken from the mixer by a syringe through an intermediate capacity and injected directly into the premises.

The measuring unit (Fig. 5b) includes counters CTC-5 (CTC-6), 12-channel recorder, and a power unit. The output device is a train oscillograph N-115 (N-700). The electronic circuit of the recorder channel is shown in Fig. 5c. To obtain numerical data on the content of $Kr^{85}$ a counting device F-588 (B-4) is connected to the recorder.

By this method, tests were performed in various premises of cubic capacity 10-230 m$^3$. Below we describe some of the results from this work.
In 1972-1973, LISI, Giproniigaz (Saratov), and Yakutmezhraigaz carried out a study of the air in buildings of Yakutsk with natural ventilation. The kitchens used stoves PG2/1-2, PG-2D, etc. The outside temperature was minus 6-46\degree C. Air exchange was measured by 1-12 counters CTC-6, temperatures by thermoresistive devices KMT-18, and the CO content by the devices UG-2 and POU-2.

In the kitchens air exchange multiplicities were 1.1-4.4 1/hr, increasing by a factor of 1.6-2.5 with open small windows. The inflowing and internal air was uniformly mixed; for different zones differed by up to 10\%. The CO concentrations were 3.6-69 mg/m\(^3\), which exceeds PDC, and is due to a lower air exchange than the normative one (see Table 1). This is caused by hermetic sealing of the premises, and the appearance at low temperatures of ice in extracting pipes and "contiguous caps" on their ends. High concentrations were sometimes observed with normal air exchange because of the large quantity of CO in the fuel. The CO content in rooms while the stoves were in operation exceeded PDC by a factor of 3-16.

The concentrations of harmful substances did not depend on the position of stoves with respect to the extracting channel because of the scattering of gaseous currents. This also explains the small role of fans in extracting channels. Thus, a fan OB-5, while increasing air exchange in a kitchen of volume 23.2 m\(^3\) by 30-50\%, decreased the quantity of CO in this volume by the same small amount.

The efficiency of over-stove hoods was found by injecting Kr\(^{85}\) into the gas main and comparing its concentration in the premises with hoods and without them. For example, hoods of
cross-section 0.22-0.49 m$^2$ placed at a height of 40-90 cm over the stove, with three normally-working burners, decreased the contents of mixtures at similar points by 1.7-2.1. Thus, hoods and a fan in the extracting channel can be regarded as means of decreasing air contamination to some extent. A radical ameliorisation of its quality can only be achieved by improving the gas-burning devices, and by decreasing the CO content of the fuel down to the normative one.

In experimental premises of volume 22m$^3$, equipped with natural and mechanical extraction, one can consider the data from comparative tests in measuring air exchange. The basis for comparison is a method which is widely used when ventilation is installed, which is based on measuring the air velocity in the extracting channel, using a winged anemometer ACO-3(B), thermoanemometer TA-8. Radio-tracer data were obtained using Kr$^{85}$, nine counters CTC-5 and the recorder described above. The results are summarised in Table 2, which also gives the range of air exchange multiplicities for various areas of the premises, integral air exchange $L$, and the relative error $\triangle L/L$ of its measurement.

The values of integral mechanical air exchange found by both methods agree within the limits of accuracy of the experiment. In other respects, the information obtained using the radio-tracer method is much more impressive: with the possibility of measuring natural air exchange and detecting the distribution of inflowing air in the premises, and also greater accuracy in measuring forced air exchange.

Conclusion.

The experience of LISI shows that radioactive tracers provide an efficient means of studying air exchange, and they can be recommended for wide use in ventilation practice.
References

Fig. 1 Minimal concentration of mixtures in air detectable by various methods.
Fig. 2. Examples of decrease of Kr$^{85}$ concentrations in premises (the arrows indicate the moment of switching on the ventilator, the figures near the graphs correspond to $\mu$, 1/hr).

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Fig. 3. The dependence of counter signals on the radius of the volume of air with tracer Kr$^{85}$.

| Theoretical curves; o — experimental curves, The values are normalised per signal unit with $R \to \infty$ and $R_0 \to \infty$. |
Fig. 4. Nomogram for detection of the initial $\text{Kr}^{85}$ concentration required to measure the air exchange multiplicity with admissible accuracy for a given duration of the experiment (counter CTC-6).
Fig 5. Circuits for the developed equipment.

a - installation for producing tracer gas;
   1 - hermetic chamber
   2 - cylinder with carrier gas (CO₂, N₂, and Ar)
   3 - piston
   4 - mixer
   5 - ampoule
   6,7 - nuts

b - block diagram of measuring equipment;
   D - detectors
   U - transformer
   N - normaliser
   I - integrator
   BP - power unit
   UPT - direct current rectifier
   R - recorder

c - electronic circuit of the recorder channel and power unit.
2-ring stoves had their burners working with nominal load, while 4-ring stoves had 2 burners with nominal load, and 2 with lower loads.

Table 1.

<table>
<thead>
<tr>
<th>Stove</th>
<th>Gas Pressure ( p ), Pa</th>
<th>Equilibrium CO Concentration ( d ), mg/m³</th>
<th>L, m³/hr</th>
<th>( \Delta L/L ),%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG2/1-2</td>
<td>2800</td>
<td>5.6</td>
<td>52.5</td>
<td>-/+</td>
</tr>
<tr>
<td>PG2/1-2</td>
<td>3200</td>
<td>36</td>
<td>44.4</td>
<td>-/+</td>
</tr>
<tr>
<td>PG-2D</td>
<td>2100</td>
<td>30</td>
<td>24.4</td>
<td>-/+</td>
</tr>
<tr>
<td>PG4/1-2</td>
<td>2100</td>
<td>9.4</td>
<td>69.5</td>
<td>+/-</td>
</tr>
<tr>
<td>PG4/1-2</td>
<td>2750</td>
<td>21</td>
<td>28.4</td>
<td>-/+</td>
</tr>
<tr>
<td>PG4</td>
<td>1300</td>
<td>8.2</td>
<td>72</td>
<td>-/+</td>
</tr>
</tbody>
</table>

Class 1"a"

* the values of \( \chi \) cannot be found

** the value of L cannot be determined since the velocity in the air tract is below the sensitivity limit of TA-8 (0.1 m/s)

Table 2.