INTERNATIONAL STANDARD 2975/VI

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION • МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ • ORGANISATION INTERNATIONALE DE NORMALISATION

Measurement of water flow in closed conduits – Tracer methods – Part VI : Transit time method using non-radioactive tracers

Mesure de débit de l'eau dans les conduites fermées – Méthodes par traceurs –
Partie VI : Méthode du temps de transit utilisant des traceurs non radioactifs

First edition – 1977-02-15

UDC 532.574.87 **Ref. No. ISO 2975/VI-1977 (E)**

Descriptors : flow measurement, water flow, pipe flow, tracer methods.

Price based on 13 pages

FOREWORD

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Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council.

International Standard ISO 2975/VI was drawn up by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, and was circulated to the member bodies in January 1976.

It has been approved by the member bodies of the following countries :

Australia
Belgium
Chile
Finland
France
Germany
India
Italy
Mexico
Netherlands
Romania
Turkey
United Kingdom
Yugoslavia

No member body expressed disapproval of the document.

Printed in Switzerland

Measurement of water flow in closed conduits – Tracer methods – Part VI : Transit time method using non-radioactive tracers

0 INTRODUCTION

This International Standard is the sixth of a series of standards covering tracer methods of water flow measurement in closed conduits.

The complete series of standards will be as follows :

- Part I : General.
- Part II : Constant rate injection method using non-radioactive tracers.
- Part III : Constant rate injection method using radioactive tracers.
- Part IV : Integration (sudden injection) method using non-radioactive tracers.
- Part V : Integration (sudden injection) method using radioactive tracers.
- Part VI : Transit time method using non-radioactive tracers.
- Part VII : Transit time method using radioactive tracers.

1 SCOPE AND FIELD OF APPLICATION

This International Standard specifies the transit time method using non-radioactive tracers for the measurement of water flow rate in closed conduits.

2 PRINCIPLE

Flow-rate measurement by the transit time method (formerly called "Allen velocity method") is based on measuring the transit time of "labelled" fluid particles between two cross-sections of the conduit a known distance apart. Labelling of the fluid particles is achieved by injecting a tracer into the flow upstream of the two measurement cross-sections (i.e. detector positions) and the transit time is determined from the difference of the mean arrival times of the tracer at each of the detector positions.

Under certain conditions (see clause 3), the row rate q_v is given by

$$q_v = \frac{V}{\bar{t}}$$

where

V is the volume of the conduit between the detector positions;

$\bar{t}$ is the transit time of the labelled fluid particles.

In general, the theoretical condition for the validity of the formula is that the measuring section be "closed to diffusion" : i.e. that the ratio of the local velocity to the longitudinal dispersion coefficient be equal at both ends of the measuring section.

In practice this condition is fulfilled when the conduit has a constant cross-section.

The value of $\bar{t}$ is obtained by measuring the difference in abscissae of characteristic points (in theory : centre of gravity, but in practice other characteristic points may be found, see 5.6) of recorded distributions, corresponding to concentration/time distributions or their integrals, obtained at each detection cross-section. The signal from the detectors shall be proportional to the tracer concentration. The value of the proportionality coefficient and hence the absolute concentration value need not, however, be known exactly.

3 REQUIRED CONDITIONS

3.1 Tracer

The tracer shall meet the general requirements defined in clause 5 of part I.

Sodium chloride is commonly used as the tracer, mainly because of the linear relationship between the conductivity of its solutions and concentration over a wide range of concentrations, and the ease with which it can be measured with an appropriate electrode system.

3.2 Mixing of tracer

The tracer must be sufficiently mixed with the flow at the first detector position for the recorded concentration/time distributions at both detectors to be adequately representative of the mean flow in the conduit (see 4.1). The selection of the positions for the injection and the detectors is controlled by the fluid velocity, tracer dispersion, and the conduit layout. The conditions for this selection are dealt with in clause 4.

3.3 Test procedure

The procedure for the preparation and injection of the concentrated solution, which in practice should be injected as rapidly as possible to minimize the duration of the concentration/time function, is covered in 5.2 and 5.3. The internal volume of the measuring section must be determined with sufficient accuracy (see 5.7). Other requirements relating to the tests and the calculation of the transit time from the data are given in clause 5.

4 CHOICE OF MEASURING LENGTH

In the transit time method, the measuring length consists of two parts :

- the length of conduit between the injection point and the position of the first detector;
- the length of conduit between detectors.

4.1 Length of conduit between injection and first detector

When the concentration of tracer C_2 at only a single point in each measurement cross-section is measured, the length of conduit between the injection point and first detector shall be equal to or greater than the mixing distance.

The mixing distance is defined as the shortest distance at which the maximum variation of $\int_0^\infty C_2\,dt$ over the cross-section is less than some predetermined value (for example 0,5 %) – see clause 6 of part I. This distance can be calculated theoretically according to 6.2.1 of part I. Figure 3 of the latter shows the measured variation of mixing distance with respect to variations in $\int_0^\infty C_2\,dt$ across the cross-section, for various injection arrangements. Methods of reducing the mixing distance are described in 6.3 of part I.

There are, however, insufficient experimental results available to relate variations in $\int_0^\infty C_2\,dt$ at the first detector position to the overall accuracy of transit time as determined from concentration measurements at single points in the measurement cross-sections.

If the measurement of concentration at each detector position represents the mean concentration in the cross-section (for example by simultaneous measurements at many points or by a detector sensitive to tracer across the cross-section), the degree of mixing required at the first detector position is not as great as that corresponding to the mixing distance. In these circumstances the necessary distance between the injection position and the first detector position may be considerably less than the mixing distance.

For example, in the application of the transit time method for the on-site testing of hydraulic machines, the use of a multipoint injection of sodium chloride and a suitable arrangement of electrode detectors can enable flow-rate to be measured accurately with a distance between injection and first detector equivalent to only seven conduit diameters (see annex A).

This application of the method has the advantage that only short lengths of conduit are required but has the disadvantage of necessitating the installation of injection points and electrode systems within the conduit.

The length of conduit between the injection position and the first detector should preferably contain no pipe fittings or sections likely to increase significantly the longitudinal dispersion of tracer at the detector positions.

Examples of such fittings and sections are valves, flow regulators and flow distribution headers.

4.2 Length of conduit between detector positions

The length of conduit necessary between the detector positions depends on the linear velocity of the fluid, the spatial dispersion of the tracer at the detector positions and the required accuracy of the measurement of transit time.

The length of straight conduit (L) between detector positions, the various ratios (p) of the transit time to the mean time for the tracer "pulse" to pass each detector position (i.e. corresponding to the passage of 99,7 % of the tracer) and the various lengths of conduit (N) between the injection and first detector positions, are related to each other by the following formula :

$$L = 4{,}25\,p\,(p + \sqrt{N})$$

where L and N are expressed in numbers of conduit diameters.

This relationship is shown graphically in figure 1.

If the concentration/time distributions are recorded on a single-channel recorder, it is necessary for the length of conduit between detectors to be greater than the mean spatial dispersion of the tracer at the detector positions so that the recorded distributions do not overlap ($p > 1$).

If a multi-channel recorder is used, this distance can be reduced, but it is necessary that for accurate measurement of transit time the length of conduit between detectors is not less than a half of the mean spatial dispersion of the tracer. For guidance, it is recommended to use in practice $p \geqslant 0{,}5$.

Care must be taken that there is no interaction between the detector points in the conduit during the passage of the tracer. For example, if sodium chloride is used as a tracer and the change in conductivity of the water is the detected parameter, then the "pulse" must not be so long that its presence is sensed simultaneously at both detector electrodes. This is achieved by having $p > 1$ in the case of a common measuring circuit.

4.3 Measuring section

For the highest accuracy of flow measurement, the length of conduit between detector positions shall consist of a straight pipe of uniform cross-section and shall contain no pipe fittings or sections where dead water zones are likely to affect the concentration/time distribution measured at the second detector.

Examples of such fittings and sections are valves, flow regulators, abrupt changes of cross-sectional area, closed-ended branch pipes or sharp bends.

The overall accuracy of the flow rate measurement is dependent on the accuracy with which the internal volume of the measuring section is determined.

4.4 Losses and additions

Additions of fluid upstream of the first detector position, of the same nature as the fluid in the conduit, do not affect the result provided that this fluid is mixed with the main flow at the first detector position.

Losses of fluid from the conduit upstream of the first detector position do not affect the result but, if the tracer is not completely mixed at the point of loss, the amplitude of the concentration/time distribution at the detector positions may be affected and its value changed by a constant factor.

Losses or additions of fluid in the length of conduit between the detector positions would cause serious errors in the measurement of flow-rate. Consequently, it is essential that the conduit between the two detector positions contain no branch connections and be free from leaks.

5 PROCEDURE

5.1 Location of injection points

The number and position of injection points located at the injection cross-section depend mainly on the length of conduit between the injection position and the first detector position and the method of measuring the tracer concentration at the detector positions (i.e. "averaging" method or single-point sample — see 4.1, 4th paragraph).

When the available length of conduit between the injection point and the first detector is less than the mixing distance, it is recommended to proceed as mentioned in 6.3 of part I.

In particular, a suitable procedure is to use a central injection against the flow or any other symmetrical arrangement within the conduit. Alternatively, the injection may be made upstream of a pump or a turbulence-generating device. If several injection points are used, the system shall be so designed as to allow simultaneous injection at all points.

5.2 Preparation of the injection solution

The concentration of tracer in the injected solution shall be uniform. Homogeneity can be achieved by means of a mechanical stirrer or closed-circuit pump.

The required concentration will depend on the volume of fluid to be injected for each measurement, the volume flow rate to be measured, the degree of longitudinal dispersion of the tracer at the detector positions and the sensitivity of the detectors. In the case of a symmetrical mode of injection, an estimate of the maximum concentration C_m of tracer observed in a straight pipe of diameter D and without obstructions at N conduit diameters downstream of the fast injection point can be obtained from the expression :

$$C_m \approx \frac{3A}{4 D^3 N^{1/2}}$$

where A is the amount, by mass, of injected tracer.

It is of interest to note that the maximum concentration does not depend on the flow rate in the conduit.

When a turbulence-generating device is positioned in the measuring length between the injection position and the first detector, the maximum concentration may be greater than that derived from the above equation.

This expression may also be used to estimate the amount of tracer to be injected for each flow measurement from a knowledge of the sensitivity of the measurement detectors. The amount of injected tracer shall be such that the tracer concentration at the detector positions is within the linear range of the detector.

5.3 Injection of concentrated solution

In order to minimize dispersion of the measured concentration/time distributions, the tracer shall be injected as rapidly as possible with no "tailing" of the injected solution from the injection tubes within the conduit. This can be achieved by any of the following means :

a) by means of injection valves at the extremity of each injection point (for example spring-loaded pop-valves); these valves shall open simultaneously, close rapidly and be leak-free;

b) by ensuring that the injected solution is flushed into the conduit by a flow of tracer-free water;

c) by breaking, with the aid of a suitable device, an ampoule containing tracer introduced into the conduit.

The tracer may be injected into the conduit by means of air or liquid pressure according to methods consistent with one of the above requirements.

It should be noted that at very high concentrations of tracer, the density of the injected solution may be significantly different from the density of fluid in the conduit. This will then affect the symmetry of the injected solution and the distribution of tracer at the detector positions.

It has been found that problems of stratification of the injected tracer solution have been avoided by adopting a lower limit of the mean velocity in the conduit. The value of this limit for satisfactory measurements to be made can be estimated from the following expression derived from laboratory tests.

$$v^2 = 0{,}2\, g\, D\left(\frac{\gamma_\mathrm{i}}{\gamma_\mathrm{w}} - 1\right)$$

where

v is the mean velocity, in metres per second, in the conduit;

g is the acceleration, in metres per second squared, due to gravity;

D is the diameter, in metres, of the conduit;

γ_i is the density of the injected solution;

γ_w is the density of the water in the conduit.

5.4 Detection of tracer

The tracer concentration may be determined from detectors situated within the conduit or from detector flow-cells sampling a flow of fluid from one or more sample points in the measurement cross-sections.

If tracer is detected at only one measuring point in each measurement cross-section, it shall be ensured that results achieved are the same for any pair of selected measuring points. When the measuring length is of uniform section between the two measuring cross-sections, selection of a pair of points on the same radius is liable to yield satisfactory results.

The difference in the time responses of the detector units, at the two cross-sections, shall be negligible compared to the transit time.

Examples of electrode arrangements which may be used within conduits for detecting sodium chloride and of typical electrical circuits are given in annex B.

5.5 Number of injections

The number of successive injections required for each measurement of flow rate depends on steadiness of the flow being measured, the random error in determining the transit time and the required overall limit of uncertainty on the measurement of flow rate.

Because in practice an absolutely constant flow rate is rarely achieved, it is recommended that at least five successive injections of tracer and associated measurements of transit time be made at each flow rate to enable an objective analysis of the random uncertainties of measurement to be made (see clause 6).

5.6 Calculation of transit time

The transit time of the tracer between detector positions may be determined by suitable graphical constructions on concentration/time distributions or their integrals recorded simultaneously with accurate timing signals from a suitable device. The transit time may be determined from the difference in abscissae of the following characteristic points of the recorded distributions from the detectors (see figure 2).

a) Centres of gravity.

b) Mid-area positions (i.e. half-areas).

The centre of gravity is the correct theoretical characteristic point in all cases. In the case of a straight conduit, the mid-area position is also a correct characteristic point.

c) Part-height positions.

The characteristic points under c) are defined by drawing a line parallel to the time axis at a level between 1/3 and 2/3 the maximum concentration. The mid-point where this line cuts the rise and fall of the pulse from the detector is then the characteristic point of that pulse. The half-height and 0,6 times the maximum concentration are two commonly used levels.

d) Other points.

The choice of other points, such as the maximum concentration, shall only be used when a rapid approximate determination is required.

Alternatively, the transit time may be determined from suitable "triggering" of an automatic timing system by the passage of tracer at each detector. The accuracy of this method depends on the method of operating the timing system and the accuracy of applied corrections for differences in the concentration/time distributions at each detector position.

Where the transit time is determined from concentration/time distributions measured by detector flow-cells, corrections shall, if necessary, be made for differences in the transit time from the measuring cross-section to the flow-cell for each detector arrangement.

5.7 Volume measurement of measuring section

The internal volume of the measuring section shall be determined either from direct capacity measurements of the capacity of the section or from measurements of the mean conduit diameter and length of conduit between the detectors.

For highest accuracy, the construction drawings must not be used for the determination of volume.

It may be convenient to choose the pipe section to be used as the measuring section before its erection and to determine its useful volume. In this case it is important that the useful volume does not change during erection.

It should be noted that the relative uncertainty on the determination of volume has as much importance as the relative uncertainty on the determination of transit time for the assessment of the overall uncertainty on the flow rate.

6 ESTIMATION OF THE UNCERTAINTIES IN FLOW RATE MEASUREMENT

Reference shall be made for the error determination to clause 7 of part I.

Generally speaking, the list of error sources is closely dependent on the various steps of the procedure described in clause 5.

6.1 The determination of the useful volume is affected by an uncertainty related to the regularity of the conduit between the measuring cross-sections, to the accuracy and to the pitch of the geometrical measurements which are carried out. The choice of a value results in a systematic error on any flow rate values calculated from this value, which can be associated with an additional random error if uncontrolled parameters, such as temperature and pressure, cause the measured volume to vary. The number of measurements of the conduit diameter shall be commensurate with the overall, required accuracy of the flow measurement.

6.2 The non constancy in both measuring cross-sections of the term $\int_0^\infty C_2\,dt$, the characteristic of mixing quality, introduces a systematic error which cannot be calculated at the present time, but whose importance is certainly much less than the maximum deviations of the term $\int_0^\infty C_2\,dt$ in both measuring sections, in particular when concentration is measured at several points of the cross-sections.

6.3 The detector defines at any time in the measuring cross-sections an approximate value of the mean tracer concentration. The value of the transit time calculated from the concentration/time curves at the positions of both measuring cross-sections is consequently affected by a systematic error which can be minimized by the improvement of the detector (number and position of detection points in the section).

6.4 It is possible for the threshold sensitivity of the detection equipment to affect the accuracy of the transit time measurement, particularly when the sensitivities of both detectors are not equal, or insufficient tracer is injected into the conduits and when dead spaces exist in the measuring section (i.e. when the ratio of the maximum signal from the detector to its threshold level is inadequate). This error can be made negligible with a suitably designed detection system, the use of sufficient tracer and the absence of dead spaces in the measuring length.

6.5 The accuracy of the transit time value is directly related to the accuracy of the pulse-emitting timing device used for the establishment of the recording time scale. The systematic uncertainty in the measurement of time caused by an inaccurate timing device is reduced as much as possible by a suitable choice of device, whilst the random uncertainty due to readability of the time scale can be reduced by increasing the transit time (i.e. increasing the distance between detectors).

6.6 The use of different methods of determining characteristic points of the pulses as described in 5.6 introduces an additional uncertainty in the determination of the mean transit time. The systematic uncertainty of this error can be decreased when the same method of analysis is used at both sections and when dispersion of tracer is short relative to the transit time. The random uncertainty of this source depends on the method of analysis and the variation in transit time caused by the unsteadiness of flow rate turbulence.

6.7 Because the measurement using transit times is not instantaneous and does not apply to an average steady flow, the fluctuations of the flow rate about the mean value are causes of random errors.

6.8 The use of the transit time method involves various uncertainties which are difficult to evaluate before the measurement. No accuracy estimation can therefore be given before the measurement. However, it can be stated that under favourable conditions an accuracy of 1 % or better can be achieved.

6.9 In all cases, the random uncertainty on transit time, which includes errors concerning the degree of mixing and the detection system, may be evaluated, *a posteriori*, by repeating measurements of a given flow rate with the same device and comparing with the estimation of random uncertainty determined by analysing the components of the uncertainty which can be expected under normal conditions of application (see 7.3.3 of part I).

7 EXAMPLE OF FLOW RATE CALCULATION

Sodium chloride is used as the tracer to measure water flow in a conduit of 2 m diameter. Electrodes are positioned in the conduit at 72 m and 172 m downstream of the injection position to measure the conductivity of the water. The tracer is injected simultaneously through four pop-valves equally spaced on a concentric pitch circle of radius 0,63 m (i.e. 0,63 of the conduit radius).

7.1 Degree of mixing at the first measuring cross-section

The first measuring cross-section is 72/2 = 36 conduit diameters downstream of the injection position. With reference to clause 6.2 and figure 3 of ISO 2975/I the variation of $\int_0^\infty C_2\,dt$ at this position is approximately 3 %. This degree of mixing is adequate for achieving an uncertainty of flow rate measurement of better than 1 % when electrode systems sensitive to a large proportion of the conduit cross-section are used.

7.2 Estimation of separation and dispersion of recorded traces

The ratio (p) of transit time to the mean time for the tracer pulse to pass each detector position is such that :

$$\frac{100}{2} = 4{,}25\,p\left(p + \sqrt{\frac{72}{2}}\right)$$

Hence $p = 1{,}56$.

Because p is greater than 1, the tracer will have left the first measuring cross-section before it reaches the second measuring cross-section so that there is no interaction between the signals from the detectors when a common electrical circuit is used. If the volume of tracer solution, of 20 g/l concentration, into the conduit during each injection is 4 l, the maximum concentration at the second measuring cross-section is :

$$C_m = \frac{3 \times 4 \times 20}{4 \times (2)^3 \times (172/2)^{1/2}} \approx 0{,}809 \text{ g/m}^3$$

This calculated value may be used to check whether the sensitivity of the measurement equipment is adequate for the required accuracy of flow rate measurement.

7.3 Volume of measuring section

The mean internal diameter of the measuring section determined from 80 separate measurements is 2,025 ± 0,002 m (95 % confidence level) and the measured distance between the measuring cross-sections is 100,2 ± 0,1 m.

The volume of the measuring section is therefore :

$$V = \frac{\pi \times (2{,}025)^2 \times 100{,}2}{4} = 322{,}7 \text{ m}^3$$

with an estimated uncertainty of

$$\pm 100 \sqrt{\left(2 \times \frac{0{,}002}{2{,}025}\right)^2 + \left(\frac{0{,}1}{100{,}2}\right)^2}$$

$$\approx \pm 0{,}22\ \%$$

7.4 Transit time

Another important source of uncertainty in the measurement of transit time results from the determination of the characteristic points. The value of this uncertainty is included in the uncertainty derived from the variation in measured transit times for a given flow rate (see below).

The transit time (t_i) corresponding to a given flow rate is obtained by comparing the distance between the centroids of the conductivity/time curves (figure 2a) with a graphically recorded time scale derived from a crystal-controlled oscillator with an uncertainty of ± 0,01 %.

7.5 Volume flow rate

The volume flow rate in the conduit during each measurement of transit time is given by :

$$q_{vi} = \frac{V}{t_i} = \frac{322{,}7}{t_i} \text{ m}^3\text{/s}$$

The mean flow rate q_v over the total measurement period of n injections is :

$$q_v = \frac{1}{n} \sum_{i=1}^{i=n} q_{v_i} = \frac{V}{n} \sum_{i=1}^{i=n} \frac{1}{t_i}$$

and the random uncertainty due to the flow variations, determination of characteristic points of the recorded traces and random uncertainties in the time scales is given by the expression :

$$t^* \sqrt{\frac{\Sigma\,(q_{vi} - q_v)^2}{n\,(n-1)}}$$

where n is the number of injections and t^* is Student's t statistic for $n - 1$ degrees of freedom.

In this example it is assumed that the mean volume flow rate is q_v m³/s, with a random uncertainty due to flow fluctuations etc. of ± 0,4 % (95 % confidence level). The overall uncertainty on the mean flow rate can be estimated by combining the component uncertainties detailed above; viz.

$$\sqrt{(0{,}22)^2 + (0{,}01)^2 + (0{,}4)^2} \approx 0{,}5\ \%$$

This example typifies the measurement of flow in favourable measurement conditions. The uncertainty of flow measurement can be considerably greater than this value if other error sources, as listed in clause 6, are present. An objective estimation of the magnitude of these uncertainties could be made by comparison with primary standards of flow measurement, either directly or indirectly, or by taking account of variations in the measuring conditions (i.e. measuring section, detector positions etc.).

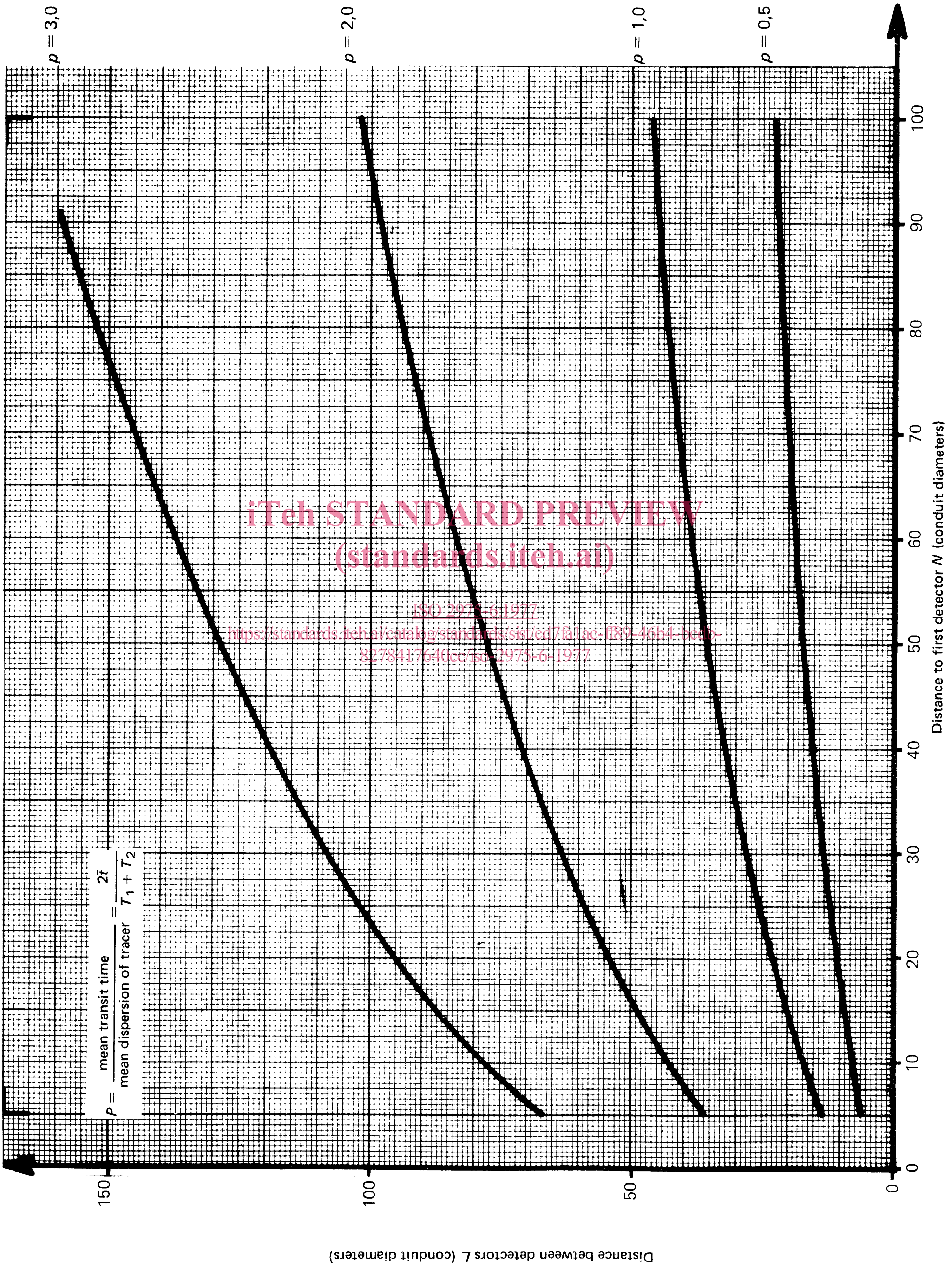

FIGURE 1 — Effect of measuring length of straight pipe on ratio of mean transit time to dispersion of tracer