INTERNATIONAL STANDARD 2975/VII

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

Measurement of water flow in closed conduits — Tracer methods — Part VII : Transit time method using radioactive tracers

Mesure de débit d'eau dans les conduites fermées — Méthodes par traceurs — Partie VII : Méthode du temps de transit, utilisant des traceurs radioactifs

First edition — 1977-12-01

UDC 532.574.87 : 621.039.85

Ref. No. ISO 2975/VII-1977 (E)

Descriptors : flow measurement, pipe flow, water flow, tracer methods, radioactive isotopes, time measurement, position.

Price based on 9 pages

ISO 2975/VII-1977 (E)

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/VII was developed by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, and was circulated to the member bodies in September 1976.

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

Belgium	India	Romania
Egypt, Arab Rep. of	Korea, Rep. of	Turkey
Finland	Mexico	United Kingdom
France	Netherlands	U.S.S.R.
Germany	Portugal	Yugoslavia

The member bodies of the following countries expressed disapproval of the document on technical grounds :

Japan
U.S.A.

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

0 INTRODUCTION

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

The complete series of standards is 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 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 flow 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, when a list of tracers generally used, with their advantages and disadvantages, is also given.

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 (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. At low Reynolds number, $Re \leqslant 5\,000$, the mixing of tracer is not sufficient and no measurement can be made.

3.3 Test procedure

The procedure for the preparation and injection of the tracer solution, which in practice should be injected as rapidly as possible to minimize the dispersion of the tracer, 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 %), C_2 being the tracer concentration in the conduit — 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, when using a γ-emitting tracer centrally injected into a conduit and detected by three scintillation detectors positioned at each measurement cross-section, flow rate has been measured accurately with a distance between injection and the first detector equivalent to only twelve conduit diameters.

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 one-half of the mean spatial dispersion of the tracer. For guidance, it is recommended to use in practice $p \leqslant 0{,}5$.

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 is free from leaks.

5 PROCEDURE

5.1 Handling of radioisotopes

The use of radioisotopes (storing, transportation, handling) shall comply with any existing statutory regulations.

5.2 Location of injection points

The number and position of injection points located at the injection cross-section depends 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, 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 consists in using a single central injection against the flow or any other device which respects the symmetry of the conduit. Injection may be also be made upstream of a pump or a turbulence-generating device. If multi-orifice injections are used, the device shall be so designed as to allow simultaneous injection at all points.

5.3 Preparation of the injected 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 degree of longitudinal dispersion of the tracer at the detector positions and the sensitivity of the detectors. An estimate of the maximum concentration C_m of tracer observed in a straight pipe of diameter D at N conduit diameters downstream of a rapid injection can be obtained from the expression :

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

where A is the amount of tracer injected.

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 position be within the linear range of the detector.

5.4 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 devices at the extremity of each injection point, for example pop-valves which open and close simultaneously and rapidly;

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

The tracer may be injected into the conduit by means of an additional pressure of gas according to methods consistent with either of the above requirements. When the tracer is injected at the pipe wall it is important that the injected fluid has a sufficient momentum to penetrate the flow;

c) by breaking, with the aid of a suitable device, an ampoule containing the liquid to be injected in the conduit.

5.5 Detection of tracer

The tracer concentration can be determined with detectors situated within the conduit or preferably outside of it, or with detector flow-cells for sampling the flow rate in the measuring cross-section.

The yield of a radiation detector is a function of the distance of the emitting particle from the detector. Where the detector is not significantly sensitive to tracer in all parts of the cross-section, consideration should be given to the degree of mixing at the first detector position.

It is always desirable to adopt identical detectors in both measuring cross-sections and to place them according to the same geometrical configuration.

The difference in response times of the detector assemblies in both sections shall be negligible with respect to the transit time.

The background noise of the detector assemblies shall be carefully measured in the absence of tracer flow in order to be able to deduce it from the gross signal. Where possible, the radiation detectors should be shielded to minimize the signal due to background.

If the mixture quality or the detectors are suspect, several detectors shall be positioned at each measurement cross-section, and the transit times measured by individual pairs of detectors shall be compared.

5.6 Number of injections

The number of successive injections required for each measurement of flow rate depends on the 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 are made at each flow rate to enable an objective analysis of the random uncertainties of measurement to be made (see clause 7).

5.7 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 times corresponding to the following positions on the recorded distribution from the detectors (see figure 2) :

a) Centres of gravity

The centre of gravity is the correct theoretical characteristics point in all cases.

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

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 intersecting each curve by a line parallel to the time axis at a level between 1/3 and 2/3 its maximum concentration. The mid-point where this line cuts the response curve of the detector is then a characteristic point. 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 concentration/time distributions at each detector position.

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

5.8 Determination of measuring section volume

The internal volume of the measuring section shall be determined either from direct 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 shall not be used for the determination of volume.

It may be convenient to choose the pipe section to be used on 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 owing to erection.

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

6 SELECTION OF TRACER

6.1 Characteristics

The general principles for the selection of tracers are given in clause 5 of part I. For radioactive tracers, the following shall also be considered :

6.1.1 *Type and energy of emitted radiations*

γ-emitting tracers are generally preferred to β-emitting tracers because the measurement of this type of radiation can be made through pipe walls and the self-absorption of radiation by the fluid is decreased. It should, however, be noted that β-emitting radio-elements are more easily handled.

6.1.2 *Maximum specific activity available*

6.1.3 *Cost*

Cost depends amongst other things on the type and characteristics of the emitted radiations on the flow to be measured, on the sensitivity of the detector assembly to be used and on the desired accuracy.

6.1.4 *Maximum permissible concentration in drinking waters*

This is an important factor in the tracer selection. Preference shall be given to the tracer with the highest ratio of the maximum permissible concentration to the concentration consistent with the desired accuracy.

6.1.5 *Half-life*

A tracer shall be chosen with the shortest possible half-life consistent with the above-mentioned conditions and with the conditions of supply, storing and measurement of the isotope, in order to minimize any effect of contamination and radiological problems associated with the handling of the isotope.

The transit time method makes it possible to use tracers with much smaller half-lives than dilution methods.

6.2 List of recommended radioactive tracers

Among the most commonly used tracers the following can be mentioned :

Isotope	Type of emitted radiation				Maximum permissible concentration 1) μCi/cm³
	Beta		Gamma		
	Energy MeV	Abundance %	Energy MeV	Abundance %	
Bromine-82 Half-life : 36,0 h	0,44	(100)	0,55 0,62 0,70 0,78 0,83 1,04 1,32 1,48	(75) (42) (28) (83) (25) (29) (28) (17)	3×10^{-3}
Sodium-24 Half-life : 15,0 h	1,39	(100)	1,37 2,75	(100) (100)	2×10^{-3}
Iodine-131 Half-life : 8,04 days	0,25 0,33 0,61 0,81	(3) (9) (87) (1)	0,80 0,28 0,36 0,64 0,72	(2) (5) (80) (9) (3)	2×10^{-5}

1) Values of maximum permissible concentration are given as a guide only and reference shall be made to national regulations.

Isotopes obtained by radioactive cows (generators)

Isotope	Half-life		Energy γ-radiation keV
ceasium-barium ^{137}Cs-^{137}Ba	^{137}Cs 30 years	^{137}Ba 156 s	662
tin-indium ^{113}Sn-^{113}In	^{113}Sn 119 days	^{113}In 104 min	390
tellurium-iodine ^{132}Te-^{132}I	^{132}Te 78 h	^{132}I 2,26 h	78

7 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.

7.1 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.

7.2 The non-constancy in both measuring cross-sections of the term $\int_0^\infty C_2 \, dt$, 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 term $\int_0^\infty C_2 \, dt$ in both measuring sections; in particular when concentration is measured at several points of the cross-section or when the radiation detectors are sensitive to flow in a large proportion of the conduit cross-section.

7.3 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 detector points in the section).

7.4 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, 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.

7.5 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).

7.6 The use of different methods of determining characteristic points of the pulses as described in 5.7 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.

7.7 Because the measurement of flow rate by the transit time method is not instantaneous and does not apply to an average steady flow, the fluctuations of the flow rate about the mean value introduce a random error.

7.8 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.

7.9 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 flow rate with the same device and comparing the uncertainty with the estimation of random error uncertainty derived by analysing the components of the uncertainty which can be expected under normal conditions of application (see 7.3.3 of part I).

8 EXAMPLE OF FLOW RATE CALCULATION

Sodium-24 (in the form of $^{24}NaHCO_3$) is used as the tracer to measure water flow in a conduit of 2 m diameter. Radiation detectors are positioned on the conduit at 72 m and 172 m downstream of the injection position. The tracer is injected simultaneously through four valves equally spaced on the pipe wall.

8.1 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 6.2 and figure 3 of ISO 2975/I the variation of $\int_0^\infty C_2 \, dt$ at this position is approximately 5 %. This degree of mixing is adequate for achieving an uncertainty of flow rate measurement of better than 1 % when radiation detectors sensitive to a large proportion of the conduit cross-section are used.

8.2 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 (with collimated radiation detectors) so that a single recorder channel may be used to record the passage of tracer.

If 10 mCi of sodium-24 is used for each injection, the maximum concentration C_m, in microcuries per cubic metre, at the second measuring cross-section is given by the formula

$$C_m = \frac{3 \times 10 \times 1\,000}{4 \times 2^3 \times \left(\frac{172}{2}\right)^{1/2}} \approx 100$$

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

8.3 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 internal volume V, in cubic metres, is therefore given by the following formula :

$$V = \frac{\pi \times 2{,}025^2 \times 100{,}2}{4} = 322{,}7$$

with an estimated uncertainty of

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

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

8.4 Transit time

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

8.5 Volume flow rate

The volume flow rate q_i in the conduit during each measurement of transit time, in cubic metres per second, is given by the formula

$$q_i = \frac{V}{t_i} = \frac{322{,}7}{t_i}$$

The mean flow rate q over the total measurement period of n injections, in cubic metres per second, is given by the formula

$$q = \frac{1}{n} \sum_{i=0}^{i=n} q_i = \frac{V}{n} \sum_{i=0}^{i=n} \frac{1}{t_i}$$

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 :

$$t^* \sqrt{\frac{\Sigma_1^n (q_i - q)^2}{n (n-1)}}$$

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 m^3/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.

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

$$\approx 0{,}5\ \%.$$

The uncertainty of flow measurement can be considerably greater than this value if other error sources, as listed in clause 7, are present. An objective estimation of the magnitude of these uncertainties could be made by comparison against primary standards of flow measurement, either directly or indirectly, and taking account of variations in the measuring conditions (i.e. measuring section, detector positions, etc.).