



BS 3680 : Part 2C : 1983

ISO 555/3-1982

UDC 532.543 : 532.574.8 : 539.16

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British Standard

Measurement of liquid flow in open channels

Part 2. Dilution methods

Part 2C. Methods of measurement using radioactive tracers

[ISO title: Liquid flow measurement in open channels — Dilution methods for measurement of steady flow — Part 3 : Constant rate injection method and integration method using radioactive tracers]

Mesure de débit des liquides dans les canaux découverts

Partie 2. Méthodes de dilution

Partie 2C. Méthodes de mesure utilisant des traceurs radioactifs

Messung der Flüssigkeitsströmung in offenen Kanälen

Teil 2. Verdünnungsverfahren

Teil 2C. Messungsverfahren mit Markierungsisotopen

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National foreword

This British Standard has been prepared under the direction of the Industrial-process Measurement and Control Standards Committee and is identical with ISO 555/3-1982 'Liquid flow measurement in open channels — Dilution methods for measurement of steady flow — Part 3 : Constant rate injection method and integration method using radioactive tracers' published by the International Organization for Standardization (ISO). It is a revision of BS 3680 : Part 2C : 1967 which is now withdrawn.

Terminology and conventions. The text of the international standard has been approved as suitable for publication as a British Standard without deviation. Some terminology and certain conventions are not identical with those used in British Standards; attention is drawn especially to the following.

The comma has been used as a decimal marker. In British Standards it is current practice to use a full point on the baseline as the decimal marker.

Wherever the words 'International Standard' appear, referring to this standard, they should be read as 'British Standard'.

Cross-references

International standard	Corresponding British Standard
ISO 772-1978	BS 3680 Methods of measurement of liquid flow in open channels Part 1 : 1979 Vocabulary and symbols (Technically equivalent)
ISO 5168-1978	BS 5844 : 1980 Methods of measurement of fluid flow : estimation of uncertainty of a flowrate measurement (Identical)

At present there are no corresponding British Standards for ISO 555/1 and ISO 555/2 which are referred to for information only.

NOTE. In figure 3 'Regulating weir' should be read as 'Regulating weir'.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

British Standard

Measurement of liquid flow in open channels

Part 2. Dilution methods

Part 2C. Methods of measurement using radioactive tracers

1 Scope and field of application

This International Standard deals with the measurement of steady flow in open channels by dilution methods using radioactive tracers with constant rate injection and integration techniques. These methods are applicable to the measurement of flow in channels where the flow conditions ensure efficient mixing of the injected solution throughout the flow.

The annex provides an example of the calculation of uncertainty in the flow rate.

2 References

ISO 555/1, *Liquid flow measurement in open channels — Dilution methods for measurement of steady flow — Part 1 : Constant-rate injection method.*

ISO 555/2, *Liquid flow measurement in open channels — Dilution methods for measurement of steady flow — Part 2 : Integration (sudden injection) method.*

ISO 772, *Liquid flow measurement in open channels — Vocabulary and symbols.*

ISO 5168, *Measurement of fluid flow — Estimation of uncertainty of a flow-rate measurement.*

3 Definitions

The following definitions shall be used for the purpose of this International Standard to complement those given in ISO 772.

3.1 activity : Number of disintegrations per unit time taking place in a radioactive sample. The unit of activity is the becquerel.

3.2 becquerel : Activity of a radioactive isotope the rate of disintegration of which is one disintegration per second.

The following multiples are used :

$$1 \text{ kBq} = 10^3 \text{ Bq}$$

$$1 \text{ MBq} = 10^6 \text{ Bq}$$

$$1 \text{ GBq} = 10^9 \text{ Bq}$$

3.3 carrier : Non-radioactive isotope of the radioactive tracer element usually added to radioisotope solutions when the concentration of the radioactive isotope of the element is so small that there is a danger of loss by adsorption on the walls of the recipient container.

3.4 classified worker : Person occupationally exposed to ionising radiations. The person is registered and is under medical surveillance. He is permitted to enter an area where the radiation dose rate exceeds a threshold imposed by national legislation.

3.5 electron volt (eV) : One electron volt is equivalent to the energy acquired by an electron accelerated by a potential difference of one volt.

$$1 \text{ eV} = 1,60 \times 10^{-19} \text{ joules}$$

The following multiples are employed :

$$1 \text{ keV} = 10^3 \text{ eV}$$

$$1 \text{ MeV} = 10^6 \text{ eV}$$

3.6 geometrical efficiency : Ratio of the number of particles or photons which enter the sensitive volume of a detector to the total number of particles or photons emitted by a radioactive source.

3.7 half-life : Time taken for the activity of a radioactive substance to decrease to one half of its initial value. Each radionuclide has a unique half-life.

3.8 isotopes : Nuclides which have the same number of protons in their nucleus, and hence the same atomic number, but differ in the number of neutrons, and hence in their atomic weights. Their chemical properties are identical.

3.9 rad : Unit of absorbed dose; $1 \text{ rad} = 10^{-2} \text{ J/kg}$ of absorbent material.

3.10 radioactive isotope, radioisotope : Nuclides whose nucleus is unstable and which on becoming stable emit energy in the form of alpha or beta particles, gamma or X rays.

3.11 radioisotopic (isotopic solution) : Solution containing radioactive isotopes.

3.12 Roentgen : Unit of exposure, corresponding to the production of two ions of opposite charges in 1 kg of air under normal temperature and pressure conditions, i.e. the liberation of $2,58 \times 10^{-4}$ coulombs in 1 kg of air.

3.13 scintillator : Solid or liquid which after absorption of electrically-charged particles emits visible or ultraviolet radiation detectable by a photomultiplier. Gamma rays produce, in this medium, interactions producing electrically charged particles which can be detected.

3.14 unclassified worker : Person who is not normally occupationally exposed to ionising radiation. This person is restricted to areas where the dose rate is below a threshold imposed by national legislation.

3.15 volumetric activity : Activity of the radioactive isotope per unit volume of a given material.

The unit is the gigabecquerel per cubic metre.

4 Units of measurement

The units of measurement used in this International Standard are those of the International System (S.I.).

5 Principle of the constant rate injection method

A solution of concentration c_1 of a suitably selected tracer is injected at constant rate q at a cross-section at the entry to the measuring reach of the channel, in which the discharge Q remains constant over the period of the test. In a second downstream cross-section of this reach, sufficiently far from the first for the injected solution to be uniformly diluted through the cross-section, the concentration due to the tracer, c_2 , is determined for a sufficient period of time and at a sufficient number of points, along the banks if it is not possible to take samples across the channel (see 9.4 and 10.4.1), to verify on the one hand that good mixing has been obtained and on the other hand that the concentration c_2 of added tracer, has reached a steady value. In these conditions the flow of tracer at the point of injection is equal to that crossing the sampling section :

$$q c_1 = (Q + q) c_2$$

hence

$$Q = q \left(\frac{c_1 - c_2}{c_2} \right) \quad \dots(1)$$

In general c_1 is much greater than c_2 and this leads to a simplification of equation (1) as follows :

$$Q = q \left(\frac{c_1}{c_2} \right) \quad \dots(2)$$

The discharge Q can therefore be determined by comparing the concentration of the injected solution with that determined in the sampling section of the channel.

NOTE — Clauses 9 and 11 on procedure and methods of analysis give all the precautions necessary (sampling, total count) to eliminate possible interferences especially due to ambient radiation, natural radioactivity c_0 of the water flowing in the channel, etc.

6 Principle of the integration method

A solution of concentration c_1 of a suitably chosen tracer is injected for a short period in a cross-section at the entry to the measuring reach of the channel, in which the discharge Q remains constant over the period of the test.

In a second cross-section of this reach, downstream by a distance equal to the mixing length (see clause 8) the concentration of added tracer, $c_2(t)$, is determined for a period of time sufficiently long to ensure that all the tracer has passed through the second cross-section.

If all the injected tracer passes through the sampling section, the following equation holds :

$$m = V c_1 = Q \int_0^\infty c_2(t) dt \quad \dots(3)$$

where

m is the mass of tracer injected;

V is the volume of solution injected;

c_1 is the concentration of tracer in the injected solution;

Q is the discharge of the stream;

$c_2(t)$ is the concentration of tracer, above background, at the sampling point during the time-interval dt .

This equation implies that the value of the integral :

$$\int_0^\infty c_2(t) dt$$

is the same at each point of the section, and the injected solution can be considered to be well mixed with the stream water if this condition is satisfied.

It can then be deduced that

$$Q = \frac{V c_1}{\int_0^\infty c_2(t) dt} \quad \dots(4)$$

NOTE — Clauses 10 and 11 give all the precautions necessary (sampling, total count) to eliminate possible interferences especially due to ambient radiation, natural radioactivity c_0 of the water flowing in the channel, etc.

7 Choice of tracer

7.1 Requirements

The tracer to be used in the injected solution must satisfy the following conditions :

- It must have a hydrodynamic behaviour identical with that of water molecules.

This property must not be altered by the temperature, by a change of chemical form, or by any possible change of phase due to an interaction with the medium. The tracer must not be present in solution in natural waters to more than a relatively small and only slightly varying amount. It must not be retained preferentially by the constituents of the channel bed (sediments, vegetation, etc.).

- b) It must be measurable with precision at a concentration below its maximum permissible concentration (MPC) specified by national regulations.

7.2 Selection criteria

7.2.1 Type

Gamma-ray emitters are preferable to β -emitters because they are more easily measured. However, it should be considered that β -emitters are easier to transport.

7.2.2 Energy

A good balance must be found between emitters which are too energetic, and therefore require extensive shielding, and those that are too weak, so that detection is difficult.

7.2.3 Cost

Depending upon the precision sought, the least expensive tracer should be chosen.

7.2.4 Half-life

The tracer with the shortest half-life should be chosen subject to the conditions of supply, storage and safety. They must not contaminate and damage the surrounding media and biosphere.

7.3 List of recommended tracers

- Bromine-82 (half-life — 36 hours, γ -emitter of 0,55 to 1,48 MeV)
- Tritium (half life — 12,26 years, β -emitter of 0,018 MeV)

The choice is subject to the consideration of the risks of contamination of ground waters that may affect their dating by the method using measurement of tritium of thermonuclear origin.

Other tracers, such as iodine-131 (half-life — 8,04 days, γ -emitter of 0,25 to 0,8 MeV) may be used in the absence of organic matter.

Other isotopes may also be used, particularly those obtainable from isotope generators, for example :

- Caesium — 137 $\rightarrow$ barium 137 (half-life 2,6 mins, γ -emitter of 0,66 MeV);
- Tin 113 $\rightarrow$ indium 113 (half-life 104 mins, γ -emitter of 0,39 MeV).

7.4 Advantages of radioactive tracers

Measurements are not affected by any physical or chemical changes of the tracer occurring in the flow, as long as such reactions do not alter the tracer's fundamental properties (see 7.1.a).

In particular, for the case of water containing suspended solids, the measurements are unaffected if settling out does not occur within the measuring reach.

Measurement of concentrations can be carried out "in situ", hence without sampling.

For γ emitting tracers of short half-life, whose carrier is innocuous, all danger of contamination rapidly disappears; there is no permanent pollution.

The cost of radioactive tracers is often less than that of other tracers, particularly for the measurement of large flows, or numerous measurements at the same site.

7.5 Special advantages of isotope generators

It is possible to obtain at the site of investigation, from a "mother" isotope of long half-life a radioactive tracer of short half-life, at low cost. When the "daughter" isotope has a sufficiently short half-life, it is possible to make repeated measurements in a closed system.

7.6 Disadvantages of radioactive tracers

- a) For each measurement it may be necessary to obtain official authorisation, which shall be given on the basis of complete technical documentation which could involve considerable expense.
- b) It is necessary that the personnel involved are especially trained, and mostly classified workers.
- c) Depending on the half-life of the tracer, there may be supply problems.
- d) Transport and injection demand special safety precautions.
- e) Complying with the safety precautions can necessitate the use of heavy containers, and these may be difficult to handle at certain sites.

7.7 Conditions for health and safety

The handling of radioactive sources, and the injection of radioactive tracers into rivers must conform with the regulations or decreed safety laws of the country concerned. This question is dealt with in the report entitled, *Guide to the Safe Handling of Radioisotopes in Hydrology*, Safety Series No. 20, International Atomic Energy Agency — Vienna 1966.

In matters of safety, the following points are to be considered :

- a) National transport regulations for the radioactive source.

b) The national safety regulations for the storage of the radioactive isotope.

c) The national safety regulations for handling of the concentrated solution of the radioactive isotopes for injection. The personnel involved must have a basic knowledge of the precautions to take, and an adequate basic training in the handling of isotopes. An instrument to check radiation rate must be available on site, in case of danger due to an accident during handling.

d) The concentration of the tracer during injection into the river must conform with the safety regulations of the country concerned and shall be maintained at the lowest possible value.

e) A check shall be made of the tracer concentration level after the measurements are taken and in case the permissible limits for concentration level are exceeded, measures shall be taken to reduce the concentration to a normal level.

In some countries, the local or national authorities must be consulted at the time of planning the investigation.

8 Choice of measuring reach

8.1 General considerations for selection of site

The measuring reach should have a length at least equal to the mixing length corresponding to the discharge being measured.

8.1.1 Conditions for mixing

The two fundamental conditions for the application of the methods are the following :

- a) all the tracer must pass through the sampling section;
- b) the tracer must be well mixed with the river water in the sampling section :

$$\int_0^{\infty} c_2(t) dt = \text{constant at all points in the section}$$

which is equivalent, in the constant rate injection method, to the more simple condition $c_2 = \text{constant}$ in the whole section for steady 'plateau' conditions.

The mixing length is the shortest distance over which the maximum relative variation of $\int_0^{\infty} c_2(t) dt$ in the section (for the method of integration) or of the concentration of tracer (for the constant rate injection method) is less than a predetermined value ε (for example 0,5 %). The mixing length therefore does not have a fixed value; it varies with the allowable variation in concentration. The smaller the allowable variation, the longer the mixing length.

To obtain the highest precision of the discharge measurement, it is necessary to have the smallest possible value of ε in the measuring section.

It is also desirable that the distance between the injection section and the sampling section should be as small as possible : this makes for economy of time and tracer.

In consequence, a reach should be chosen in which the river is as narrow and as turbulent as possible, free of dead water zones, and with numerous transverse currents, favouring lateral mixing which is the most difficult to obtain; grassy and vegetation covered zones should be avoided, as should zones where the river divides into several arms (see figure 1).

The sampling section should be chosen in a narrow zone where there are no back-currents or dead water.

8.1.2 Special cases

- a) Inflows of water into the measuring reach

Measurements can be made where there is an inflow of water (tributaries or springs) into the measuring reach provided only that good mixing is achieved at the sampling section.

The measured flow then includes the intermediate water inflow.

- b) Abstraction or leakage from the measuring reach

If there is a leakage or abstraction between the injection section and the sampling section, the result will be questionable, except where the leakage or abstraction is perfectly known and is located at a point where good mixing is already achieved; in this case the analysis of samples will lead to the value of the river discharge upstream from the leakage or abstraction, and not to the value of the discharge at the sampling section.

- c) Dead water zones

If there are any dead water zones, these may detain tracer and release it only very slowly after the passage of the principal pulse, so that the measuring time is considerably prolonged. It is necessary to continue sampling until all the tracer collected in the dead water zones has passed the downstream sampling cross-section. An error of measurement may therefore arise, since a considerable amount of tracer may pass through the downstream section at the end of the test, when concentrations are too low to be measured.

8.2 Preliminary tests

These are meant to specify the mixing length and the corresponding optimum duration of injection.

8.2.1 Determination of the length of the measuring reach

A first test can be made by using a strong dye such as fluorescein. A concentrated solution of this dye can be injected for a relatively short time, at a point upstream of the measuring reach. Study of the diffusion of the solution will make it possible to determine whether there are dead water zones or

other zones of loss of tracer, and give a first indication of the minimum distance which must separate the injection point and a suitable sampling section.

This procedure may be improved by performing a continuous injection of fluorescein, rhodamine B or WT, the transverse distribution of which is studied at different sections downstream with the aid of a portable fluorimeter. The use of dye tracers for preliminary tests shall conform with national and local regulations relating to the release of such substances into the environment.

The minimum distance of good mixing can be estimated theoretically in a very approximate way for measurements in a channel or river.

8.2.1.1 Measurements with a line injection

Where injection is made in a channel of uniform flow by means of a device distributing the injection flow rate over the whole width of the channel in proportion to the flow rate in each elementary vertical section, the minimum length of good mixing, L , is given by the formula (in SI units)

$$L = 10 r d \quad \dots(5)$$

where

d is the mean depth;

r is the ratio of the mean velocity to the friction velocity.

The value of r will be taken to be

$$r = \sqrt{\frac{8}{\lambda}} \quad \dots(6)$$

where λ is the coefficient of the universal formula giving the head loss per unit length

$$H = \frac{\lambda}{4 R_h} \times \frac{v^2}{2g} \quad \dots(7)$$

where

H is the head loss per unit length;

R_h is the hydraulic radius;

v is the mean velocity;

g is the acceleration due to gravity.

NOTE — It is possible to express r in the following manner :

$$r = \frac{K R_h^{1/6}}{\sqrt{g}} = \frac{C}{\sqrt{g}} \quad \dots(8)$$

where

K is the Strickler coefficient, which is a function of the roughness;

R_h is the hydraulic radius;

C is Chezy's coefficient.

The Chezy coefficient can be calculated by the formula

$$C = \sqrt{g} \sqrt{\frac{8}{\lambda}} \quad \dots(9)$$

This theoretical formula has recently been the subject of satisfactory experimental verification.

8.2.1.2 Measurement with a centre point injection

For a point injection on the axis of the flow, the minimum mixing distance can be estimated by formula (10) which has not yet been checked by systematic experiment :

$$L = \frac{0,13 \bar{b}^2 C (0,7 C + 2 \sqrt{g})}{g \bar{d}} \quad \dots(10)$$

where

$\bar{b}$ is the mean width of the wetted cross-section in the measuring reach (in metres);

$\bar{d}$ is the mean depth of water in this reach (in metres).

It is emphasised that the length obtained from formula (10) can only be used as a first indication and that the length to be used must be established by practical trials. For example, as this formula is based on a single point injection in a straight reach, the length obtained may be shorter if multiple injections are performed in the injection section.

Furthermore, some tests show that this formula (10) gives too small a value for the mixing length for small streams about 5 m wide, and too great a value for rivers about 50 m wide.

8.2.2 Duration of injection

8.2.2.1 Constant rate injection method

The duration of injection shall be such that a steady concentration regime is established in the sampling section for a sufficient length of time, usually 10 to 15 min.

The duration of injection, which is generally related to the degree of turbulence, will vary directly with the length of the measuring reach and with the extent of dead water zones and inversely with the mean water velocity.

For a given discharge, observations of the moment of arrival and disappearance of tracer in each section may be plotted as the curves 1 and 2 in figure 2. On the other hand this experiment can be used to determine the minimum mixing length (see 8.1).

The selected sampling section corresponding to the mixing length consistent with the precision sought is represented by the straight line S.

If it is desired to obtain, at the selected sampling cross-section, a steady regime for a time Δt , it is necessary to add the time Δt to the time t corresponding to the disappearance of tracer in