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Measurement of water flow in closed conduits — Tracer methods — Part III : Constant rate injection method using radioactive tracers

*Mesure de débit de l'eau dans les conduites fermées — Méthodes par traceurs —
Partie III : Méthode d'injection à débit constant, utilisant des traceurs radioactifs*

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FOREWORD

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It has been approved by the Member Bodies of the following countries :

Australia	Italy	Turkey
Belgium	Netherlands	United Kingdom
Czechoslovakia	Romania	U.S.S.R.
France	Spain	Yugoslavia
Germany	Switzerland	

The Member Body of the following country expressed disapproval of the document on technical grounds :

U.S.A.

Measurement of water flow in closed conduits – Tracer methods – Part III : Constant rate injection method using radioactive tracers

0 INTRODUCTION

This International Standard is the third 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 constant rate injection method using radioactive tracers for the measurement of water flow rate in closed conduits.

2 PRINCIPLE

Flow rate measurement by a constant rate injection method is based on a comparison between the concentration C_1 of a tracer continuously introduced with a known volume rate of flow q , and the concentration of samples C_2 taken at some place beyond the distance¹⁾. The mixing distance is defined as the shortest distance at which the variation in concentration of the tracer over the cross-section is less than some pre-determined value (for example 0,5 %). (See clause 6 of part I.)

The tracer rate at the injection point is equal to the rate at which it passes the sampling point :

$$q C_1 + Q C_0 = (Q + q) C_2$$

Where C_0 is the initial concentration in the stream which is flowing at the rate Q .

Hence :

$$Q = q \frac{C_1 - C_2}{C_2 - C_0} \quad \dots (1)$$

Generally C_1 is much greater than C_2 which leads to a simplification of equation (1) as follows :

$$Q = q \frac{C_1}{C_2 - C_0}$$

When C_2 is much greater than C_0 , the equation can be reduced still further to

$$Q = q \frac{C_1}{C_2}$$

Flow rate Q can thus be determined by comparing the concentration of the injected solution with the concentration of samples removed from the conduit.

3 REQUIRED CONDITIONS

3.1 Tracer

For the constant rate injection method the tracer shall meet the general requirements defined in 5.1 of part I. A list of generally used tracers is given in 5.1.2 of part I and their advantages with respect to non-radioactive tracers are stated in 5.2.1.1 and 5.2.1.2.

3.2 Duration of injection

The duration of injection shall be such that stable concentration conditions are established at all points of the measuring cross-section over a sufficient period of time.

1) Another method can be contemplated which would not involve sampling.

Constant concentration shall be obtained for a period of at least several minutes.

Determination of the injection duration

A suitable duration of injection may be determined by a preliminary investigation involving the instantaneous injection of a dye such as fluorescein or a radioactive tracer. Curves 1 and 2 of figure 1 may be plotted for a given flow rate from the observation of the moment when the tracer (dye or activity) appears and disappears in each cross-section.

If it is required to achieve steady conditions for a period of time Δt in a selected measuring cross-section S, it is sufficient to add this period of time Δt to the time t_1 corresponding to the disappearance of the tracer at this point (i.e. on curve 2) and to plot through the resulting point C a curve 1' similar to curve 1 characteristic of the appearance of the dye (or activity). The ordinate at the origin of this curve gives the duration of the injection to obtain a concentration level of duration Δt at cross-section S.

In practice, to obtain a concentration level of duration Δt at cross-section S, a calculation is made of the minimum required period of injection by adding to the value of Δt the time $t_2 = AB$ taken by the instantaneously injected tracer to pass through S.

The time interval t_1 between the beginning of the injection and the establishment of stable conditions can be read from curve 2 (ordinate of point B) and is directly obtained by measuring the time interval between the instantaneous injection and the tracer disappearance in cross-section S.

In the case of central injection, straight measuring length and turbulent flow, $t_2 = AB$ may be estimated from the relationship

$$t_2 = \frac{6}{U} \sqrt{\frac{DX}{2}}$$

where

- U is the mean velocity of the flow;
- X is the distance to the injection point;
- D is the conduit diameter.

The fraction of maximum concentration remaining after time t_2 as given by this formula is 0,3 %.

It is possible, when no preliminary injection is made, to check the appearance of the concentration level, and therefore the minimum injection time, by continuously sampling the flow and measuring its count rate, with the apparatus used for the measurement. This procedure enables the concentration variation to be determined as a function of time.

4 CHOICE OF MEASURING LENGTH

4.1 Mixing distance

This is defined in 6.1 of part I and may be calculated theoretically according to 6.2.1 of part I. Figure 3 of part I indicates the measured variation of the actual mixing distance according to the required accuracy in the case of central injection and in the case of three other injection methods. Methods for reducing the mixing distance are described in 6.3 of part I.

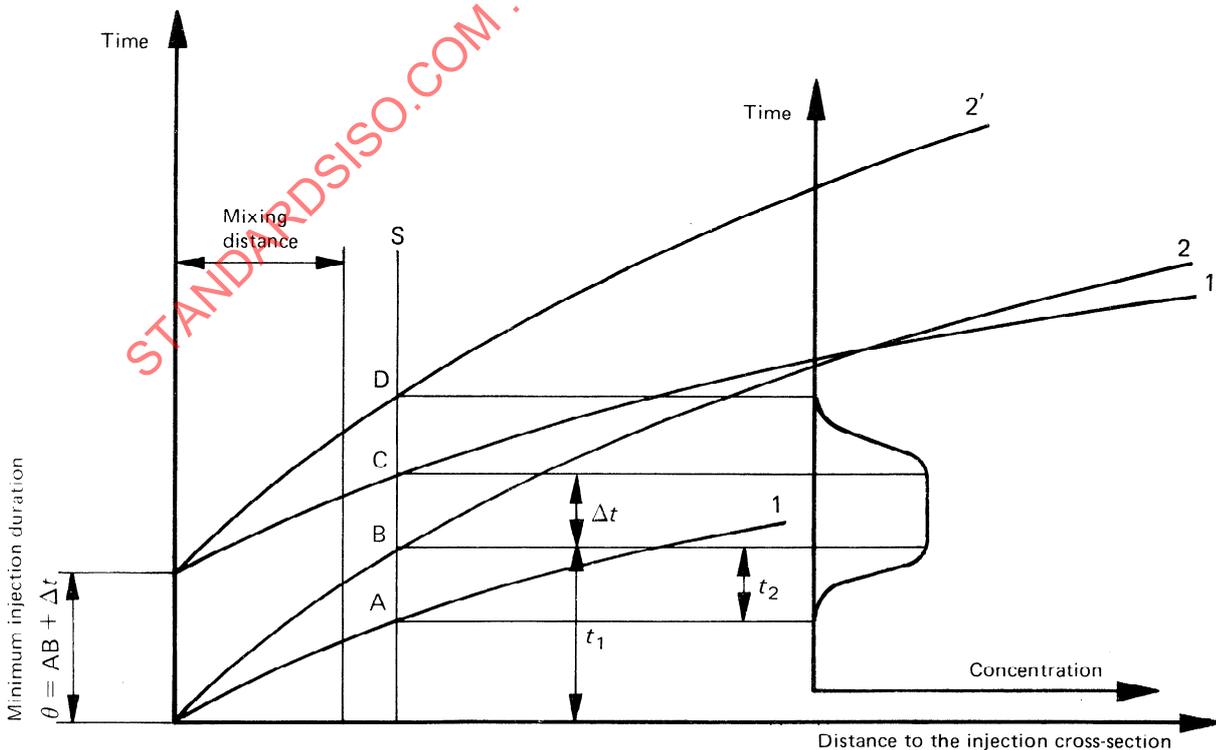


FIGURE 1 – Determination of the duration of injection

4.2 Experimental checking

It is seldom possible in conduits to check experimentally, in a large number of cross-sections, the homogeneity of the mixture and the duration of the tracer passage resulting from an instantaneous injection.

In practice, therefore, the experimentation consists of

- a) determining the minimum period of injection in the measuring length chosen by a preliminary test (see 3.2);
- b) checking, where possible, at the time of the measurement, that the mixture is homogeneous by taking samples from at least two points of the measuring cross-section. In the case of high accuracy measurements (for example 0,2 %), it is necessary to check the homogeneity of the mixture, prior to the measurement itself, when a doubt exists on the quality of this mixture;
- c) studying, whenever possible by taking samples from another cross-section further downstream, whether there are any systematic differences between the mean concentrations at the two measuring cross-sections. In particular, this method permits verification that the injected tracer is not absorbed in the measuring length either by entrained products in the liquid or by the conduit walls.¹⁾

4.3 Losses and additions

The losses and additions of the same liquid as that in the measuring length do not affect results provided certain conditions are met as described in 6.5.1 of part I.

5 PROCEDURE

5.1 Handling of radio-isotopes

The use of radio-isotopes (storage, transportation, handling) shall comply with any existing statutory regulations.

5.2 Preparation of the concentrated solution

It is essential for the injected solution to be homogeneous. Homogeneity of the solution can be obtained by vigorous mixing, by means of a mechanical stirrer or a closed-circuit pump. It is advisable to prepare the injection solution in a separate container from the supply container with water filtered using an appropriate procedure. However, if mixing is carried out in the supply container, the latter shall have sufficient capacity so that it is not necessary to add liquid or tracer during the injection. The solution shall be taken at a certain level above the bottom of the container, and every precaution shall be taken so that undissolved particles of the tracer are not carried in the solution injected. In the

case of an injection of long duration, provision shall be made as required to avoid a variation in time of the solution concentration (for example by evaporation under the influence of the ambient temperature).

To minimize possible adsorption effects with the radioactive tracer it is advisable to add to this solution a carrier constituted by a certain amount of non-radioactive substance identical to that containing the radioactive tracer.

5.3 Injection of the concentrated solution

The concentrated solution shall be injected into the conduit at a constant rate and for a sufficient duration to ensure a satisfactory period of constant concentration at the measuring cross-section.

The injection may be made by means of a positive displacement pump. It shall be possible to check the following :

- that the injection system is always free from leaks;
- that the injection rate is constant over the whole injection duration.

5.4 Measurement of injection rate

The measurement of injection rate shall be based on the measurement of the basis quantities of mass, length, time, directly involved in the definition of the quantity of flow.

The injection system shall be calibrated before and after the tests. The mean value of injection rate shall be used in the calculation of flow rate provided that the two calibrations do not differ by more than a value consistent with the overall required accuracy of flow measurement (for example 1 %).

When the injection is carried out by means of a positive displacement pump driven by a synchronous motor, which is the normal method, the checking of flow rate consists in fact in the measurement of the frequency of the electrical supply.

5.5 Sampling

5.5.1 Samples

Samples shall be taken :

- from the conduit, to verify that the background concentration of tracer in the flow system is constant;

1) See 5.1 of part I.

- from the conduit, to determine the tracer concentration in the measuring cross-section, to check that the tracer concentration is homogeneous in the sampling cross-section and to check the concentration level (see 4.2);
- from the injected solution, to check the homogeneity of the tracer concentration (see 5.2);
- from the injection solution, to compare the concentration of tracer in the injected solution with the concentration of tracer in the samples taken from the conduit.

In practice, samples shall be taken under the following conditions :

- two or three samples of the liquid flowing in the conduit upstream from the injection section during injection or, when variations of the background concentration along the meaning length are suspected, in the sampling cross-section before and after the passage of the solution;
- three to five samples of the injected solution at the outlet of the injection equipment immediately before and after the injection period;
- at least five samples of the diluted solution in the conduit, if possible from at least two points in the measuring cross-section (at least three at the same point), distributed in time during the passage of the solution.

5.5.2 Sampling equipment

Sampling shall be carried out during the period of constant concentration, the beginning of which may be determined by continuously measuring the count rate of the water in the conduit.

5.6 Diluted solutions

The concentration of the injected solution cannot be measured directly and it is necessary to reduce it approximately to that of the samples taken from the conduit.

To this effect a sample of the concentrated injection solution is diluted by gravimetric methods (precision balances) or volumetric methods (flasks, calibrated pipettes or micro-burettes) with water taken from the conduit upstream from the injection section or before the tests.

From the product of the measured count rates and dilution factors, it is possible to estimate the magnitude of any random errors in the dilution and measurement procedures.

6 METHODS OF ANALYSIS AND COMPUTATION

6.1 Determination of flow rate

The dilution ratio of the injected solution in the water flowing in the conduit is determined by measuring the count rates from the diluted solutions and the samples under the same conditions of detector geometry and with the same count rate measurement equipment.

As ratio C_1/C_2 may for example have a value between 10^4 and 10^6 it is necessary to dilute the injected solution sample to compare neighbouring concentration samples, situated in the linear operating range of the detection unit.

If D is the dilution factor defined by the ratio of the concentration C_1 to the concentration of tracer in the diluted solution, the dilution ratio of the injected solution in the water flowing in the conduit C_1/C_2 is given by $D \frac{N_1}{N_2}$

where N_1 and N_2 are the mean count rates from the diluted solutions and samples respectively.

The flow rate can then be determined from :

$$Q = qD \frac{N_1}{N_2} \dots (3)$$

(The injection flow rate being very small in comparison with the flow rate to be measured.)

Due to the half-life of the isotope, the count rates N_1 and N_2 vary with time according to an exponential law. However, this decay does not affect the ratio N_1/N_2 .

If N_1 and N_2 are measured at different times, corrections for the decay must be made.

In practice the count rates N_1 and N_2 are not obtained directly; a background count rate is obtained from the natural radioactivity in the water from the conduit, from cosmic radiation and from electrical "noise" in the detection system.

This background count rate (n_0) can be measured directly from samples of water taken from the conduit preferably upstream of the injection section during the test or possibly before the tests.

If the measurement of count rates from the diluted solutions and the samples containing the tracer results in count rates n_1 and n_2 .

We have

$$N_1 = n_1 - n_0$$

$$N_2 = n_2 - n_0$$

and equation (3) now becomes :

$$Q = qD \frac{n_1 - n_0}{n_2 - n_0} \dots (4)$$

This method of calculation assumes that the conduit water taken upstream from the injection point is used to constitute the injection solution and its dilution for the determination N_1 . If water from another source is used, the corresponding background noise n_e shall be determined as indicated above, and equation (4) becomes :

$$Q = qD \frac{n_1 - n_e}{n_2 - n_0} \dots (5)$$

If the dilution factor (D) is obtained gravimetrically, a correction is required for the density differences of the conduit water, the injected solution and the samples.

If the dilution of an aliquot sample of the original solution is carried out with water at temperature t_i , the general equation shall be used :

$$Q = qD \frac{n_1 - n_e}{n_2 - n_0} \times \frac{(\rho_i)_{t_i}}{(\rho_d)_{t_d}} \times \frac{(\rho_c)_{t_m}}{(\rho_c)_{t_c}} \dots (6)$$

where

ρ_i is the density of the injected solution;

ρ_c is the density of the conduit water;

ρ_d is the density of the water used for the dilution;

t_i is the temperature of the injected solution;

t_c is the temperature of the conduit water;

t_m is the temperature of the conduit water sample during its measurement;

t_d is the temperature of the diluted solution during its measurement.

The introduction of this correction entails the determination of densities at given temperatures. The most appropriate method shall be adopted for this determination with regard to the required accuracy of measurement under the test conditions and with the available equipment.

When the count rates from all the diluted solutions are measured on one apparatus and if one of these solutions is measured on the apparatus used to measure the count rates from the samples, a correction factor (R) may be necessary in the calculation of flow rate if there is evidence that an error has been introduced in the dilution procedure.

This correction factor shall be the ratio of the mean product of dilution factor and count rate obtained from measurements of all the diluted solutions to the product of dilution factor and count rate obtained from measurement of the diluted solution transferred to the apparatus used for the sample measurement.

6.2 Counting equipment

The choice of the counting equipment for the volume of sample to be measured and the type of shielding necessary to allow for the background count rate shall be made with the view to obtaining the best signal to noise ratio (N_i/n_0) consistent with the required accuracy of measurement.

For γ -emitting tracers the counting equipment shall preferably include a scintillation detector containing a NaI crystal connected to a scaler to record the counts obtained over the measurement period.

Measurements of N_1 , N_2 , n_0 shall be carried out under the same geometric conditions of samples relative to the detector, the same sensitivity of detector and at the same temperature.

Thermal equilibrium of the detector shall be attained before commencement of the measurements and account must be taken of any electronic dead time of the equipment.

The use of a single set of counting equipment avoids certain systematic errors in the comparison of count rates. The use, when possible, of several sets of counting equipment to measure count rates from both the samples and diluted solutions enables a check to be made on the measurements.

6.3 Method of counting

The samples taken upstream from the injection point or before the tests shall be counted before, during and after the measurement of samples containing tracer in order to determine the background count rate n_0 and to check that the counting equipment is not contaminated.

The constancy of sensitivity of the detector shall be checked by periodically measuring the count rate from a radioactive source (for example cobalt-60) throughout the period of measuring the count rates from the samples and diluted solutions.

It is recommended that at least three dilutions (and preferably more) be made of the injected solution and that at least five conduit samples (and preferably more), taken at different times during the test, shall be measured. It should also be checked that a constant concentration level was achieved.

For the most accurate measurements, a χ^2 test should be carried out before the measurements using an auxiliary radioactive source of long half-life (for example cobalt-60) in order to check the stable operation of the detection unit.

6.4 Measurement of half-life

The count rate from one of the diluted solutions (see 5.6) shall be measured periodically (at least four times) during the period of the tests, in order to determine the half-life of the radioactive tracer for use in the calculation of flow rate.

6.5 Presence of silt

If silt is present in the conduit water, preliminary tests shall be carried out to establish that adsorption of tracer on to the silt does not occur (see 5.1 of part I).

If adsorption of tracer is feared, the measurement may be possible in certain cases subject to special precautions to achieve in particular the same accuracy.

Experiments carried out to establish the effect of silt in suspension in the conduit water on the measured count rate from a sample, have shown that the count rate is unaffected by a small percentage of silt. Larger amounts of suspended silt may be allowed if water from the conduit is used in the diluted solutions (see 5.6) and as far as possible, any silt present in the sample bottles shall be allowed to settle or be removed by decanting the water in the counting bottles; silt removed in this way is not included in the flow measurement.

7 CHOICE OF RADIOACTIVE TRACERS

7.1 Characteristics

The general criteria for choosing tracers for flow rate measurements apply to radioactive tracers.

The specific characteristics of the latter, as specified below, shall also be considered :

Type and energy of the emitted radiations

γ -radiation emitters are preferred to β -radiation emitters because of the greater ease of measurement and the increased counting efficiency resulting from the decreased effect of self-absorption of radiation in the sample. However, due regard shall be taken of the ease of transporting β -emitting isotopes.

Maximum specific useful activity available

Cost

The cost of the tracer depends on the type and characteristics of the emitted radiation, the flow rate to be measured, the sensitivity of the detection system and the required accuracy of measurement.

Maximum permissible concentration in drinking waters

This is an important factor in the choice of a suitable tracer.

In this respect, the tracer with the highest ratio of maximum permissible concentration to the concentration consistent with the required accuracy shall be used for the tests. The tracer used shall always comply with any existing statutory regulations applying to the site of the measurements.

Half-life

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

7.2 List of recommended radioactive tracers

A list of tracers which can be used is given in 5.1.2 of part I. Among the most useful tracers are those shown below.

Isotope	Type of radiation				Maximum permissible concentration
	Beta radiation		Gamma radiation		
	energy MeV	abundance %	energy MeV	abundance %	
Bromine-82 half-life 36,0 h	0,44	(100)	0,55	(75)	$3 \times 10^{-4} \mu\text{Ci/cm}^3$
			0,62	(42)	
			0,70	(28)	
			0,78	(83)	
			0,83	(25)	
			1,04	(29)	
			1,32	(28)	
Sodium-24 half-life 15,0 h	1,39	(100)	1,37	(100)	$2 \times 10^{-4} \mu\text{Ci/cm}^3$
			2,75	(100)	
Iodine-131 half-life 8,04 days	0,25 0,33 0,61 0,81	(3) (9) (87) (1)	0,80	(2)	$2 \times 10^{-6} \mu\text{Ci/cm}^3$
			0,28	(5)	
			0,36	(80)	
			0,64	(9)	
			0,72	(3)	

8 EXAMPLE OF CALCULATION OF FLOW RATE

8.1 A measurement was carried out in the following way :

- Injection of a sodium-24 solution by a positive displacement pump driven by a synchronous motor connected to a 50 Hz electrical supply.
- Dilution of five samples of the injected solution with water from the conduit; determination of the dilution ratios by a gravimetric method; analyses in a counting equipment (A) and in a counting equipment (B) for one of them (No. 3).
- Collection of ten samples to be analysed in a counting equipment (B).

8.2 Calculation of injection volume rate of flow

- Injection rate at 50 Hz (q') 2,099 cm³/s
- Mean frequency (f) 49,96 Hz
- Density of injected solution at injection temperature (ρ_i) 1,016 g/cm³
- Density of water at the conduit pressure and temperature (ρ_c) 1,002 g/cm³

$$q = 2,099 \times \frac{49,96}{50}$$

$$= 2,097 \text{ cm}^3/\text{s} \text{ or } 2,097 \times 10^{-6} \text{ m}^3/\text{s}$$

8.3 Calculation of dilution ratios of solution samples

Diluted solution No.	1	2	3	4	5
Sample of injected solution	0,848 5 g	1,108 5 g	0,980 7 g	0,972 2 g	0,851 0 g
Sample of injected solution + water from first dilution	945,5 g	901,0 g	914,5 g	923,3 g	942,7 g
Sample after first dilution	1,025 5 g	1,165 4 g	0,883 0 g	1,023 5 g	0,992 4 g
Sample after first dilution + water	3 835,0 g	3 837,0 g	3 844,5 g	3 852,0 g	3 821,0 g
Density of conduit water	0,998 2 g/cm ³				
Density of water used for dilution	0,998 2 g/cm ³				
$D =$ volume dilution rate $\times 10^{-6}$	4,167	2,676	4,060	3,574	4,265

8.4 Calculation of count rate from samples of diluted solution with equipment (A)

Sample	Time at end of counting from zero min	Counting period min	Recorded counts	Decay time from datum from reference time 173,7 min min	Corrected counting rate ¹⁾ per minute
Conduit water	5	16,67	7 059		
Standard cobalt-60	46 86	16,67 16,67	414 027 412 992		
Conduit water	105	16,67	6 907		
Diluted solution No. 1	182 210	16,67 16,67	506 013 495 375	0 28	30 001,0 29 999,8 mean 30 000,4
Diluted solution No. 2	259 312	16,67 16,67	740 489 709 932	77 130	46 849,1 46 846,0 mean 46 847,5
Standard cobalt-60	337	16,67	413 344		
Conduit water	369 388	16,67 16,67	7 225 7 378		
Diluted solution No. 3	449 473	16,67 16,67	424 157 417 882	267 291	30 814,7 30 878,9 mean 30 846,8
Diluted solution No. 4	513 539	16,67 16,67	458 060 449 295	331 357	35 006,3 34 973,3 mean 34 989,9
Diluted solution No. 5	612 640	16,67 16,67	358 162 350 401	430 458	29 404,4 29 380,2 mean 29 392,3

1) The correction includes the corrections

for dead time : 4,25 μ s,

for background count rate (Co) : 426 counts per minute,

for decay time from a datum arbitrarily selected : 173,7 min.

Calculation of corrected count rate for solution No. 3 on equipment (B)

- Recorded counts during counting period of 40 min 883,438 (see 8.6)
- Decay time from datum 498 min (in minutes) 218,3
- Corrected count rate (correction of equipment B) $C_1 = 25 712,6$ counts per minute

8.5 Checking of the validity of the dilution method used for injected solution samples

This check may be carried out by comparing the spread of the values corresponding to the product of the count rate and dilution ratio about the mean value on the one hand and about the value estimated from counting statistics only on the other hand (F-variance ratio test).

Diluted solution No.	1	2	3	4	5	Mean	Standard deviation S
Dilution ratio (X 10 ⁻⁶)	4,167	2,676	4,060	3,574	4,265		
Product of count rate by dilution ratio (X 10 ⁻¹¹)	1,250 2	1,253 6	1,252 4	1,250 5	1,253 6	1,252 1	0,11 %

The standard deviation estimated from counting statistics only is approximately given by :

$$\sigma = \frac{100 \%}{\sqrt{N_{\text{mean}}}}$$

where N_{mean} is the average count number recorded for each diluted solution. In the example $\sigma = 0,10 \%$.

The maximum value of the ratio S/σ below which there is no significant difference between both standard deviations at a 95 % confidence level may be derived from the distribution of the variance ratios for this confidence interval, i.e. :

Number of samples	3	4	5	6	7
Maximum value of variance ratio for a 95 % confidence level	1,41	1,40	1,38	1,36	1,34

$S/\sigma = 0,11/0,10$ is less than 1,38, which allows the conclusion that the dilution method does not introduce an abnormal spread. Were the difference significant, then a correction factor R would have to be applied to the result obtained on the selected diluted solution (counted with the same equipment B as for the collected samples); this factor is defined in 6.1.

8.6 Calculation of count rate from collected samples with counting equipment (B)

Sample	Time at end of counting from zero min	Counting period min	Recorded counts	Decay time from datum : 498 min min	Corrected count ¹⁾
Standard cobalt-60	474,5	10	263 454		
Conduit water	485,3	10	3 896		
S1	496,4	4	81 234	- 3,6	79 539 ²⁾
S3	503,1	4	81 610	3,1	80 330
S5	508,8	4	81 625	8,8	80 698
S7	514,1	4	81 279	14,1	80 685
S9	519,8	4	80 742	19,8	80 491
S11	525,8	4	80 460	25,8	80 576
S13	531,7	4	80 154	31,7	80 633
S15	536,9	4	80 355	36,9	81 163
S17	543,2	4	79 531	43,2	80 718
S19	548,5	4	78 633	48,5	80 109
Standard cobalt-60	695,7	10	263 845		
Diluted solution No. 3	736,3	40	883 438	218,3	25 712,6
Conduit water	751,9	10	4 025		
Mean			80 600		
$C_2 - C_0 =$ mean corrected count rate			20 150 counts per minute		
Standard deviation of count rates for samples in % of mean value			0,35 %		

- 1) Corrections are of the same type as for counting with equipment (A)
- 2) It is apparent that this sample was taken before constant concentration of tracer was obtained and consequently is not used for flow calculation.

8.7 Calculation of flow rate

$$\begin{aligned}
 Q &= \frac{C_1}{C_2 - C_0} \times D \times q \times \frac{\rho_i}{\rho_c} \\
 &= \frac{25\,712,6}{20\,150} \times 4,060 \times 10^6 \times 2,097 \times 10^{-6} \times \frac{1,016}{1,002} \\
 &= 11,02 \text{ m}^3/\text{s}
 \end{aligned}$$

(values of C_1 and D used relate to diluted solution No. 3)

9 ESTIMATION OF ERROR

9.1 General

The estimation of error is to be carried out according to the requirements of clause 7 of part I.

The calculation of flow rate from a measurement by dilution following the constant rate injection of a radioactive tracer is carried out in several stages : injection rate – dilution ratio – counting of diluted and collected solution samples, and it is therefore convenient to estimate the limit errors for each stage assuming correct application of the method, then to check, whenever possible (that is when several measurements are available), whether the recorded spread is consistent with the expected accuracy.

9.2 An example of error calculation

Application to the example of flow rate calculation as given in clause 8.

9.2.1 Systematic errors

These cannot be estimated with accuracy but careful injection, collecting, counting analysis and dilutions, and correction formulae for electrical supply frequency variations, for dilution and counting systematic errors or for water density variation with temperature, practically guarantee that the systematic error of the result is very small, for example less than 0,2 %. It should be noted that the components of error applicable to the equipment used or to checkable operations such as dilution of injected solution samples, may be made as small as required by calibration and use of correction factors. However, errors which are more difficult to check can be introduced by the dilution process occurring with the conduit.

9.2.2 Random errors

Error in injection rate

- limit error of frequency measurement : $E_f = 0,05 \%$
- limit error of density measurement : $E_d = 0,1 \%$
- limit error of pump discharge rate : $E_{dr} = 0,05 \%$

Overall limit error for 95 % confidence level :

$$2\sqrt{(0,05)^2 + (0,10)^2 + (0,05)^2} = 0,25 \%$$

Error in mean count rate of collected samples

- a) Limit error due to counting of C_2

$$E_s = \frac{t \times S_s}{\sqrt{n_s - 1}} = \frac{2,3 \times 0,35}{\sqrt{8}} = 0,3 \%$$

where

t is the Student factor for a 95 % confidence level;

$(n_s - 1)$ is the number of degrees of freedom (see 7.3.4 of part I);

S_s is the standard deviation of the count rate series about the mean value as a percentage of the mean;

n_s is the number of samples.

- b) Limit error due to counting of C_0

$$E_b = \frac{200}{t} \frac{\sqrt{N}}{C_2 - C_0} \%$$

where

t is the counting period;

N is the total number of counts accumulated from background samples;

$C_2 - C_1$ is the difference between the mean count rate of the samples taken upstream of the injection position.

This error is negligible in the selected example.

The error of mean sample count rate is therefore :

$$\sqrt{E_s^2 + E_b^2} = E_s \approx 0,3 \%$$

Part of this error is due only to statistical uncertainty associated with the recorded count number. Its value for different numbers of samples and counts is given in figure 2.

Error in dilution ratio

In the example described, the comparison of the spread of : count rate \times dilution ratio products and of the expected spread estimated from statistics only (see 8.5) showed that the deviation was not significant. The error in dilution ratios is therefore negligible. If this deviation had been significant, it would have been necessary to calculate the error in correction factor R , an error which is made up of an error in the mean product and a counting error in the product associated with the diluted solution used in the particular measurement.

Error in the count rate of the diluted solution used during the test

$$E = 2 \times \frac{100}{\sqrt{N}} = 2 \times \frac{100}{\sqrt{883\,438}} \approx 0,2 \%$$

Error due to uncertainty in half-life

The error in the decay factor corresponding to an error in half-life is approximated by the expression :

$$\text{Error } E_H \text{ per hour of decay period} = 69,3 \frac{dT_{1/2}}{(T_{1/2})^2}$$