Flow Measurement Using the Dye Dilution Technique

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Abstract

The Performance and Testing Department of Ontario Power Generation, Electricity Production Services Division, offers a less common but valuable technique for water flow measurement. Our technique utilizes fluorescent dye and a very precise procedure which provides highly accurate results. The recommended dye for this method is the fluorescent dye, Rhodamine WT. The dye is detectable and stable in very low concentrations, non-toxic, resistant to adsorption, mixes readily in water, and is not usually present in natural water systems. Its fluorescence level which is proportional to its concentration in water is accurately measured with a precision fluorometer.

The method involves four key functions:

- Injection of dye into the system
- sampling the water downstream
- preparation of a "standard" of known dilution and
- comparison of the "sample" and the "standard"

The technique has proven to be inexpensive, accurate and adaptable. The test needs no elaborate facilities and equipment can be set up quickly and simply. The test results are extremely accurate, and can reliably achieve results with an accuracy of ± 1.5%. In addition, the system is extremely adaptable and has a wide range of applications including: condenser circulating water pumps, hydraulic turbines, heat exchangers, service water pumps and service water systems.

The application of our dye dilution technique was developed approximately 30 years ago and has been used with success since the early 1970's. At that time, the technique was proven on condenser circulating water pump performance acceptance tests. Since then, we have conducted water flow tests to verify the performance of some of the large turbines in Ontario Power Generation's hydroelectric power stations.

We have also conducted performance tests for the Electric Power Research Institute at hydraulic power plant Kootenay Canal in British Columbia and Grand Coulee Dam in Washington. These tests were conducted as part of a research project supporting the revision of the ASME performance test code for hydraulic turbines.

This method of flow measurement is also included in the International Standard IEC 41 1991-11 and will be included in the next revision of ASME PTC 18 Hydraulic Turbines. Both of these codes provide procedures for determining field performance testing of hydraulic turbines and of pump/turbines operating with water in either the turbine or pumping mode, by measuring flow rate (discharge), head, and power, from which operating efficiency may be determined.

Introduction

The increase in size of Condenser Circulating Water Pumps required for the newer generation of nuclear and fossil fuelled power stations first commissioned during the 1960's, posed serious problems where the measurement of flow was concerned. Up to this point in time, these flows were measured with the conventional propeller type current meters, located on a cross-piece spanning two diameters of the flow conduit. With the increase in conduit diameter, and the requirement for one hundred diameters of upstream straight section to give uniform flow at the point of measurement, serious physical limitations were foreseen. Furthermore, the problems normally associated with the installation of these current meters such as system de-watering, isolation and installation of mechanical structures became significant enough to warrant investigation into other methods of measurement for large water flows.

The use of water soluble tracers in the study of water flow is not a new scientific concept. Over a hundred years ago, in France, Schloesing introduced ammonium sulfate into a stream, and chemically analyzed water samples taken downstream to determine the dilution that had occurred. The possibilities for adaption to flow measurement, which such a scheme provoked, produced a significant interest, and since then a great many tracing techniques have been devised and used, both in Europe and the United States. While the United Kingdom has concentrated on the use of radioactive isotopes for use as tracers, specifically Sodium 24, here in North America, the tendency has been to use soluble chemical tracer dyes, particularly those belonging to the fluorescent family.

A system has been developed by the Performance and Testing Department of Ontario Power Generation to the stage where the method is now accepted by pump suppliers to Ontario Power Generation as an equally accurate and practical alternative to the current meter system previously used. The theory of this method is included in the International Standard IEC41, Field Acceptance Tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines. It will also be included in the next revision of ASME PTC 18 Hydraulic Turbines.

Development of the System

Measurement of the flow by the constant rate injection system is based on a comparison between the concentration of a tracer injected at a known rate, with the concentration of samples extracted from some location, sufficiently remote from the injection point to ensure good mixing. The two major areas of development required in the initial stages were:

1) Accurate detection
2) Constant rate injection

Accurate detection requires the combination of a suitable dye and a sensitive instrument for detection. Early on in the development program, after consultation with specialists in the field of dye tracing, it was decided to use Rhodamine WT fluorescent dye as the tracer, and a fluorometer as the detecting equipment. The development of this dye by a leading chemical manufacturer, and the fluorometer by Turner Designs, made the detection process practical at very low concentrations.

The constant rate injection problem initially proved more difficult to solve. Early experiments with commercially available chemical metering pumps proved unsuccessful, mainly due to the fact that these, although accurate in dispensing a specific quality over time, did so in slugs, consistent with their reciprocating action.

A volumetric plexiglass cylinder, calibrated to discharge at a known rate by use of compressed air, was somewhat more successful, but dependant to a large extent on the pressure downstream of the injection nozzle for consistency of results.

In the United States, Mariotte Vessels, floating syphons and pressurized tanks had been used successfully in streams and open channels, but it was considered that these would suffer the same problems as our volumetric cylinder when used to inject the tracer into the suction bell of large circulating water pumps.

The United Kingdom Atomic Energy Authority (UKAEA) was finally contacted, and they undertook to manufacture and supply a unidirectional positive displacement injection pump, similar to that used in their radioactive tracer program. This pump has a calibrated accuracy of ±0.05% on measured volume delivered, and has fulfilled the stringent requirements for constant rate and volume characteristics necessary for the accurate determination of flow.

With some measure of confidence, confirmed by experiments in connection with these two fundamental requirements, a developmental program was initiated to identify the techniques, procedures and precautions which would ensure accuracy and repeatability, at least equal to existing methods of flow measurement. Several tests were carried out at Ontario Power Generation's power stations in conjunction with current meters, and the correlation of results have been excellent. During the developmental period, several significant characteristics of the method, system and procedure were identified leading to the formation of techniques and procedures, which now form the basis for the flow measurement using the dye dilution method.

Theory

The dye dilution technique for the measurement of flow is suitable for "once through" pumping systems, where no recirculation takes place. It involves the injection of Rhodamine WT fluorescent dye at one point in a system, and the removal of samples of water from a point further downstream, after the dye has been thoroughly mixed with the water.

Flow rate is established from the determination of the dilution of the injected dye.

If this dye is injected at a constant rate, the relationship between the concentration and flow is, in its simple form:

$$Q_1 C_1 = Q_2 C_2$$

Where: Q_1 = dye injection rate
C_1 = concentration of injected dye
Q_2 = flow rate to be determined
C_2 = concentration of dye in water stream

Thus: $Q_2 = Q_1 \times C_1 / C_2$
C_1 / C_2 is known as the "dilution factor", DF

The dilution factor of a solution can not be measured directly, but can be determined by comparing its fluorescence (which is proportional to its concentration) with that of a specially prepared "standard solution" of precisely known dilution. This standard solution is prepared by diluting a sample of the injected dye by the same amount as it will undergo when injected into the system. The fluorescence level of a test sample and the standard solution are measured in a fluorometer, and the dilution factor of the test sample is determined as follows:

$$DF_t = DF_s \times F_s / F_t$$

Where: DF_t = dilution factor of test sample
DF_t = dilution factor of standard solution
F_t = fluorescence level of test sample
F_s = fluorescence level of standard solution

The flow to be measured is then:

$$Q_2 = Q_1 \times DF_s \times F_s / F_t$$

Figure 1 shows a schematic representation of this technique.

Equipment and Material

The principal items of equipment are:

- Dye injection pump
- Fluorometer
- Rhodamine WT fluorescent dye
- Constant temperature bath
- Miscellaneous laboratory equipment

Dye Injection Pump

It is essential that the dye be injected into the system at a constant and precisely known rate. The pump used by Ontario Power Generation is shown in Figure 2. It is a single stroke positive displacement pump, with synchronous motor drive. The flow was determined by calibration to be 0.12513 litres/ min. ±0.05%, and for one charge delivers approximately 1.2 litres over a ten minute injection period. Flow rates of one half or one quarter of this can be selected by means of variable gear ratios in the drive mechanism.

Fluorometer

The fluorometer measures the intensity of the fluorescence of a sample of water with dye in solution. This can be regarded as a relative measurement of the dye concentration, since fluorescence varies linearly with concentration.

When the injected dye is passing the sampling point, the fluorometer, which is fitted with a "flow-through" door, allows continuous monitoring of a stream of water passing through the fluorometer.

During the analysis of the test samples, it is used to measure the relative concentrations of test samples and standard solutions for determination of the flow. For this function, an interchangeable door is installed which permits measurement of grab samples in a small test tube or cuvette.

Rhodamine Wt Dye

This dye, which was developed specifically as a water tracer dye, is manufactured by Crompton and Knowles, and is available in liquid form in 20% solution only. It is detectable by the fluorometer in concentrations lower than 0.01 parts per billion, but in practice, concentrations of about 10 parts per billion are aimed for. Of the many fluorescent dyes available, Rhodamine WT is amongst the most widely used for this type of application, because of its low absorptive tendencies, and other advantageous characteristics. In concentrated form it is a dark red colour, but in the concentration used no visible coloration of the water is apparent. It is also non-toxic and chemically unreactive.

Constant Temperature Bath

The fluorescence level of Rhodamine WT dye is extremely sensitive to temperature change, and varies inversely with temperature at a rate of about 2.6% per degree Celsius. Consequently, the test samples and standard solutions must be at the same temperature during the analysis phase of a test. This is achieved by means of a constant temperature bath, in which the samples and standards are immersed prior to analysis.

The water in the bath is constantly circulated by means of a small circulating pump, and it is possible to maintain the temperature of all samples to within 0.1^{o}C of each other. The fluorometer door, into which cuvettes of samples are placed for analysis, is also circulated with water from the bath to maintain a uniform temperature.

Miscellaneous

The only equipment required is for the preparation of the standard solutions. This comprises standard laboratory glassware, i.e. beakers and 1000 ml. volumetric flasks, and a laboratory weigh scale capable of measurement to 0.001 grams.

Test Procedure

The test procedure comprises of the following five steps:

1. Preparation of the injection solution
2. Injection of the dye
3. Sample collection
4. Preparation of standard solutions
5. Analysis

Preparation of Injection Solution

In theory, any concentration of dye may be used for injection. In practice however, a good operating range for the fluorometer is with a concentration of about 10 ppb, and the injection solution is prepared so that the final concentration after injection into the system will be about 10 ppb. The solution is prepared by diluting stock Rhodamine WT dye with water from the system under test. Tap water is not used, and it should be noted that chlorine reduces fluorescence.

The dilution is calculated as follows:

$C_1 = Q_2 / Q_1 \times C_2$

Where:

C_1 = concentration of injection solution (ppb)
C_2 = desired concentration after injection (= 10ppb)
Q_1 = injection pump flow rate (litre/sec)
Q_2 = anticipated flow being measured (litre/sec)

Thus: $C_1 = Q_2 / Q_1 \times 10$ ppb

i.e. the injection solution should contain

$$\left(Q_2 / Q_1 \times 10 \times 10^{-7} \right) \text{ \% dye}$$

Since the stock dye is only 20% solution, the injection solution should contain

$$\left(Q_2 / Q_1 \times 5 \times 10 \times 10^{-7} \right) \text{ \% of stock solution}$$

Example:

If $Q_2 = 5000$ /sec
And $Q_1 = 0.002$ litre/sec
The injection solution should contain

$$\left(5000 / 0.002 \times 5 \times 10 \times 10^{-7} \right) = 12.5\%$$ of stock dye or 125 ml of dye per litre of solution.

Sufficient solution is prepared in a sealable container and thoroughly mixed.

Injection

A schematic arrangement of the injection system is shown in Figure 3. Two methods of injection may be employed:

1. If direct and close access to the injection point is possible, the dye is injected into the system through a probe inserted part way into the duct. A spring-loaded non-return valve on the end of the probe prevents back flow water between injection periods.
2. If the point of injection is unaccessible, such as the suction bell of a submerged suction wet-pit pump, then during construction, a tube is fitted leading from the pump room to the pump suction bell. This tube may be of considerable length, and its volume may be significant in relation to the low rate of the injection pump. Problems may then arise because of the dilution of the dye in this line between injections and the inability of the injection pump to effectively purge the line, due to its extremely low flow rate.

This is overcome by providing a continuous secondary water supply of about 5 litres per minute down the injection line, and injecting the dye into this secondary supply. This has the effect of transporting the dye into the pump suction in the minimum of time. The quantity of this supply is not critical, but it should be maintained constant, as any fluctuation would effectively change the rate of injection. Chlorinated tap water in not used, as chlorine may reduce the fluorescence. The supply is usually taken from the local service water system.

Injection of dye for the measurement of flow in hydraulic turbines involves extremely large volumes of flow and sometimes short mixing lengths. This problem has been resolved the installation of temporary injection grids. These grids are used to increase the number of injection nozzles and therefore facilitate the mixing process. The dye is also injected with the nozzles facing upstream to further improve the mixing of the dye.

Sample Collection

The sampling location is selected to allow sufficient distance from the injection point to ensure complete mixing of the injected dye. This is generally achieved in about one hundred diameters of straight pipe, but may be greatly reduced by the presence of bends or other causes of flow disturbance in the line.

The sampling equipment is shown in Figure 4. Its sole purpose is to determine when the dye is passing the sampling point, and when the sample should be taken. No analysis is donicke at this point.

As dye is being injected at a point upstream, a continuous sample of water is bled from the system and passed through the fluorometer (and then to drain) at a rate of about 4 litres per minute. As the injected dye reaches the sampling point, and passes through the fluorometer, the chart recorder coupled to the signal output of the fluorometer will indicate an increase in fluorescence. When this level stabilizes at a plateau, indicating uniform dye concentration, a sample is bled off slowly over a period of about five minutes. The samples are collected in 500 ml. dark glass bottles, and stored away from light until analysis is conducted. As the last of the slug of dye passes the sampling point (after about 10 minutes) the chart trace will return to zero. A typical chart recording is shown in Figure 5.

Observation of the chart trace will indicate the degree of mixing achieved. A straight, level plateau indicates good mixing, while erratic trace indicates incomplete mixing, in which case sampling should be done further down stream.

Preparation of Standard Solutions

The standard solutions are prepared in the laboratory by diluting a sample of the injection solution to the same concentration as is anticipated in the samples. If tests have been conducted at several flow rates (as in the case of a pump test), then a standard solution is prepared to match each flow. The water used to prepare the standards is taken from the system under test, so that they have the same levels of turbidity, pH, etc. as the test samples. Chlorinated tap water is not used to prepare standard solutions.

The dilution factor for preparing the standards will be:

$$DF = Q_2 / Q_1$$

Where: Q_1 = flow rate of dye injection pump
Q_2 = flow rate to be measured

Since this factor is of large magnitude, frequently in order of several millions, the standard solutions are prepared by "serial dilution", in which each solution is diluted in turn until the correct factor is attained.

A four serial dilution is usually performed, in which the dilution factor for each successive dilution will be:

$$DF_p = \left(Q_2 / Q_1\right)^{1/4}$$

Example:

If Q_1 = 0.002 litre/sec
Q_2 = 5000 litre/sec

$$DF_p = \left(5000 / 0.002\right)^{1/4} = 39.764$$

That is, each 1000 ml. flask of solution will contain

$$\left(1000 / 39.764\right)$$

or 25.148 ml. of the previous solutions.

For greater accuracy the dye is weighed out and topped up to the 1000 ml. mark. As a safeguard against errors while preparing the standard solutions, two sets are prepared independently, and their agreement is checked during the analysis.

Analysis

The arrangement for equipment for the analysis is shown in Figure 6. Test samples and standard solutions are stored in the temperature equalizing bath until all temperatures have stabilized and are uniform to within 0.2^{o}C.

The fluorescence of a test sample and a standard solution is determined by inserting a cuvette of each into the fluorometer. This is repeated six times, and the average value obtained for each.

It should be noted that the fluorescence level is an arbitrary value, and need not be calibrated, since it is only the ratio of the two fluorescence levels which is required.

The flow is then determined as follows:

$$Q_2 = Q_1 \times DF_s \times F_s / F_t$$

Where:

Q_1 = flow rate of dye injection pump (litre/sec)
Q_2 = flow rate to be measured (litre/sec)
DF_s = dilution factor of standard solution
F_s = fluorescence level standard solution
F_t = fluorescence level of test sample

Accuracy of Measurement

Comparative tests were conducted during an acceptance test of a condenser circulating water pump, where the flow as measured by the dye dilution method was compared with that measured simultaneously by current meters, calibrated to within ±1.0%. Eight tests were conducted at various flows ranging from 82000 usgpm to 12400 usgpm, and the average deviation of the flow measured by dye dilution, from that measured by the current meters was +0.7%. A statistical analysis which took into account the ±1.0% accuracy of the current meters, indicated a total uncertainty of ±1.6% (95% confidence level).

Error analysis conducted on results from other tests, which took into account the systematic and random errors for each parameter involved, indicate an uncertainty of ±1.1% (95% confidence level).

Field Experience

With the present methods and equipment, flow in excess of 63 m^3/s (1,000,000 usgpm) can be measured. This capability could be increased by an increase in the rate of dye injection.

On-site performance and diagnostic tests using the dye dilution method have been conducted on the following pumps and systems:

STATION	CAPACITY
Lennox GS - CCW Pumps (8)	5.43 m^3/s (86000 usgpm)
Bruce NGS - CCW Pumps (2)	12.93 m^3/s (205000 usgpm
Bruce HWP - Lift Pumps (2)	11.61 m^3/s (184000 usgpm)
Bruce HWP - CW Pumps (2)	5.36 m^3/s (85000 usgpm)
Douglas Pt. - Process Water Pumps (2)	0.82 m^3/s (13000 usgpm)
Pickering NGS - CCW Pumps (2)	11.99 m^3/s (190000 usgpm)
Bruce NGS - Moderator Heat Exchange Study (2)	0.55 m^3/s (8700 usgpm)
Galt Energy Systems HGS	4.90 m^3/s (173 cfs)
Decew Falls HGS	10.5 m^3/s (370 cfs)
Elliot Chute HGS	20 m^3/s (20 cfs)
Kakabeka Falls HGS	20 m^3/s (706 cfs)
Ontario Power HGS	21.8 m^3/s (706 cfs)
South Falls HGS	3.1 m^3/s (110 cfs)

Advantages of the Technique

- There is no need for down time of equipment before and after tests, with the attendant isolation and de-watering for the installation and removal of test equipment.
- No modification to the system is necessary for the installation of orifices or other types of flow meters.
- There is no interference with the system operation due to pressure drops caused by flow measurement devices.
- Diagnostic tests can be conducted at very short notice, since no test preparations are necessary, other than to ensure that injection and sampling points are available.

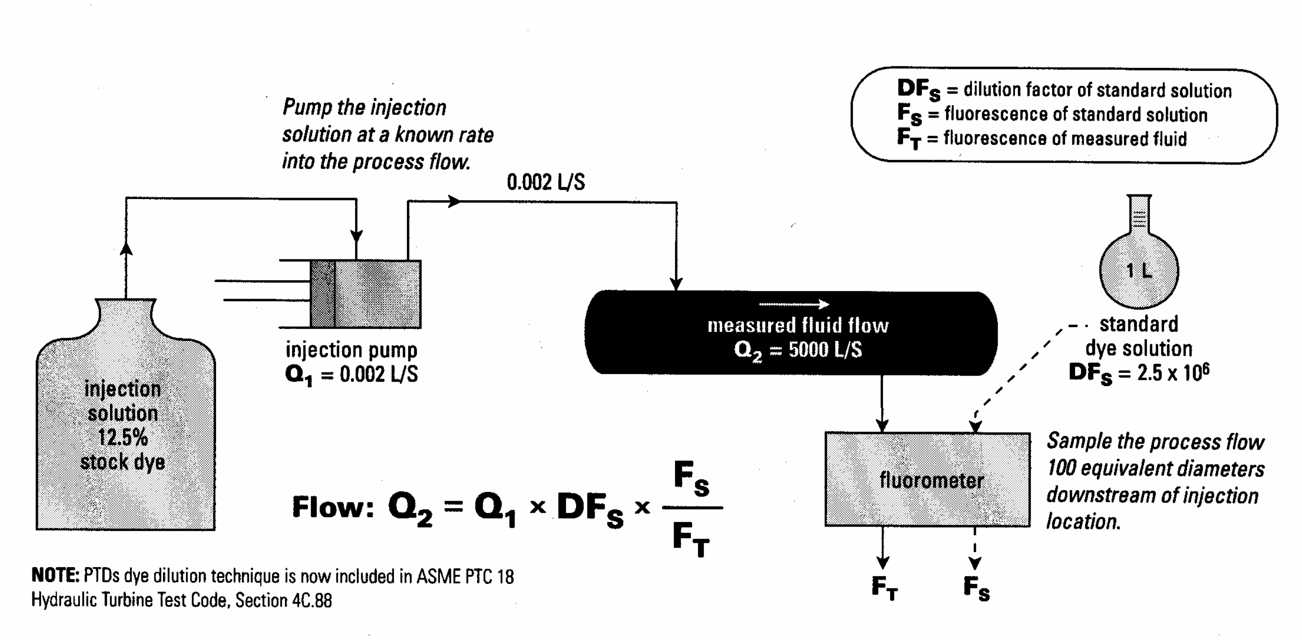

Figure 1
Dye Dilution Water Flow Measurement Technique

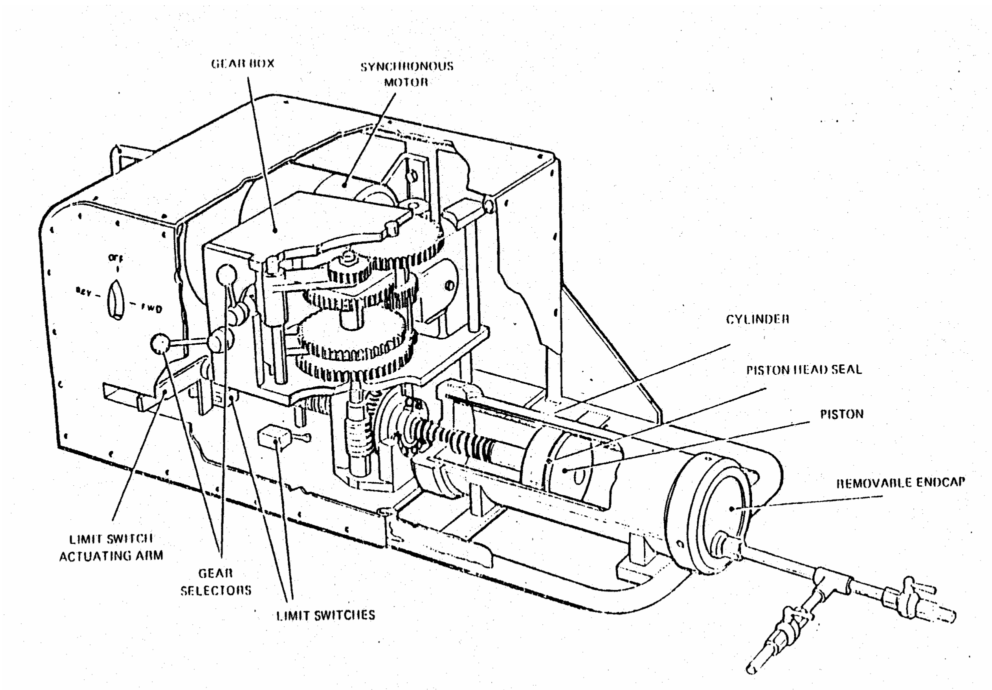

Figure 2
Diagram of Constant-Rate-Injection Pump

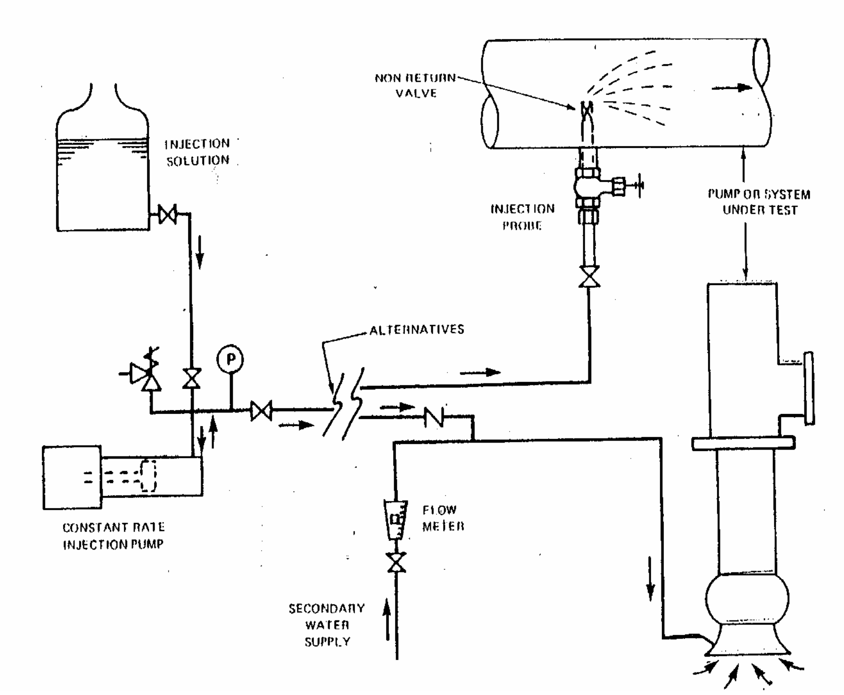

Figure 3
Arrangement of Injection Equipment

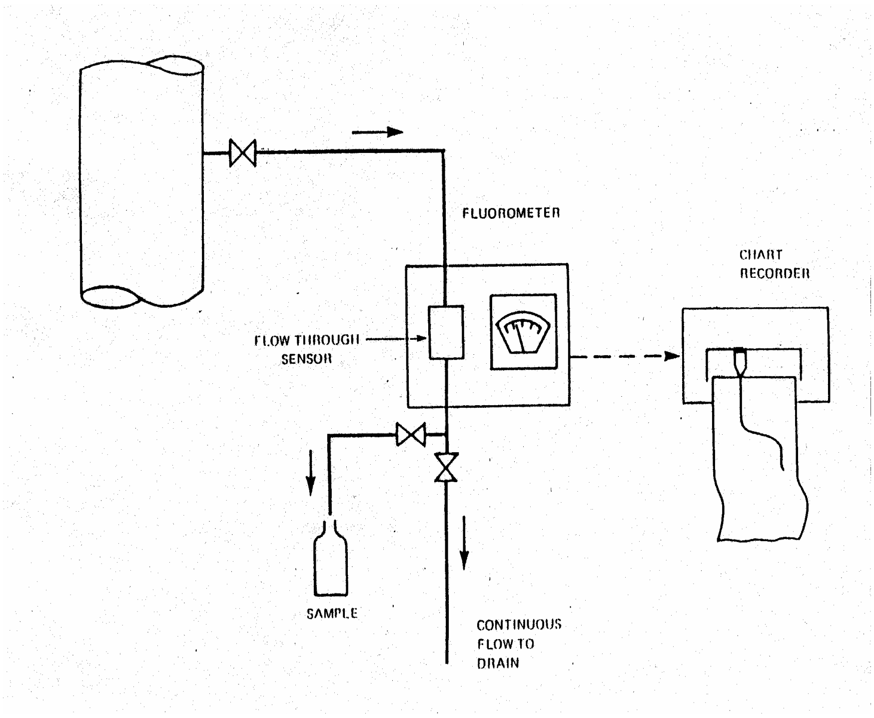

Figure 4
Arrangement of Sampling Equipment

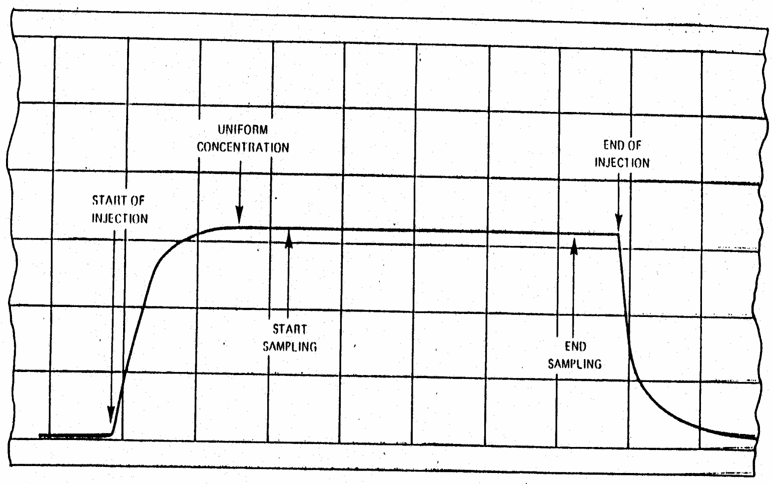

Figure 5
Typical Chart Recording During Sampling

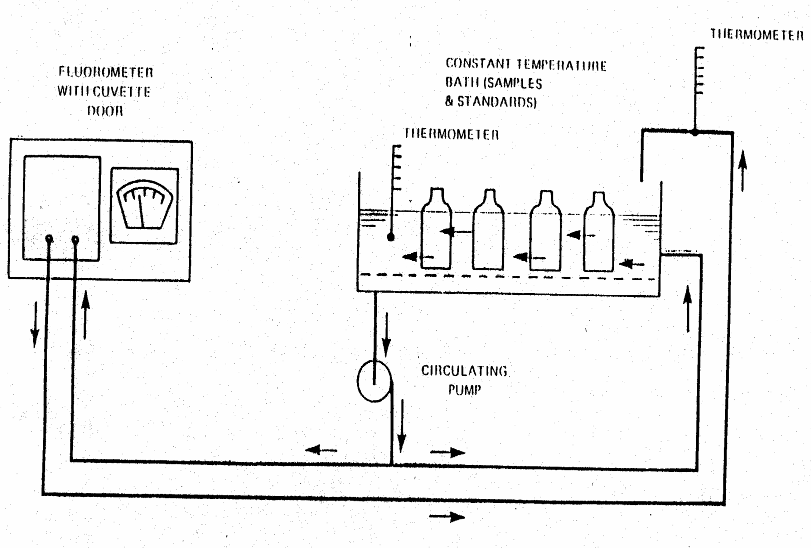

Figure 6
Arrangement of Analysis Equipment

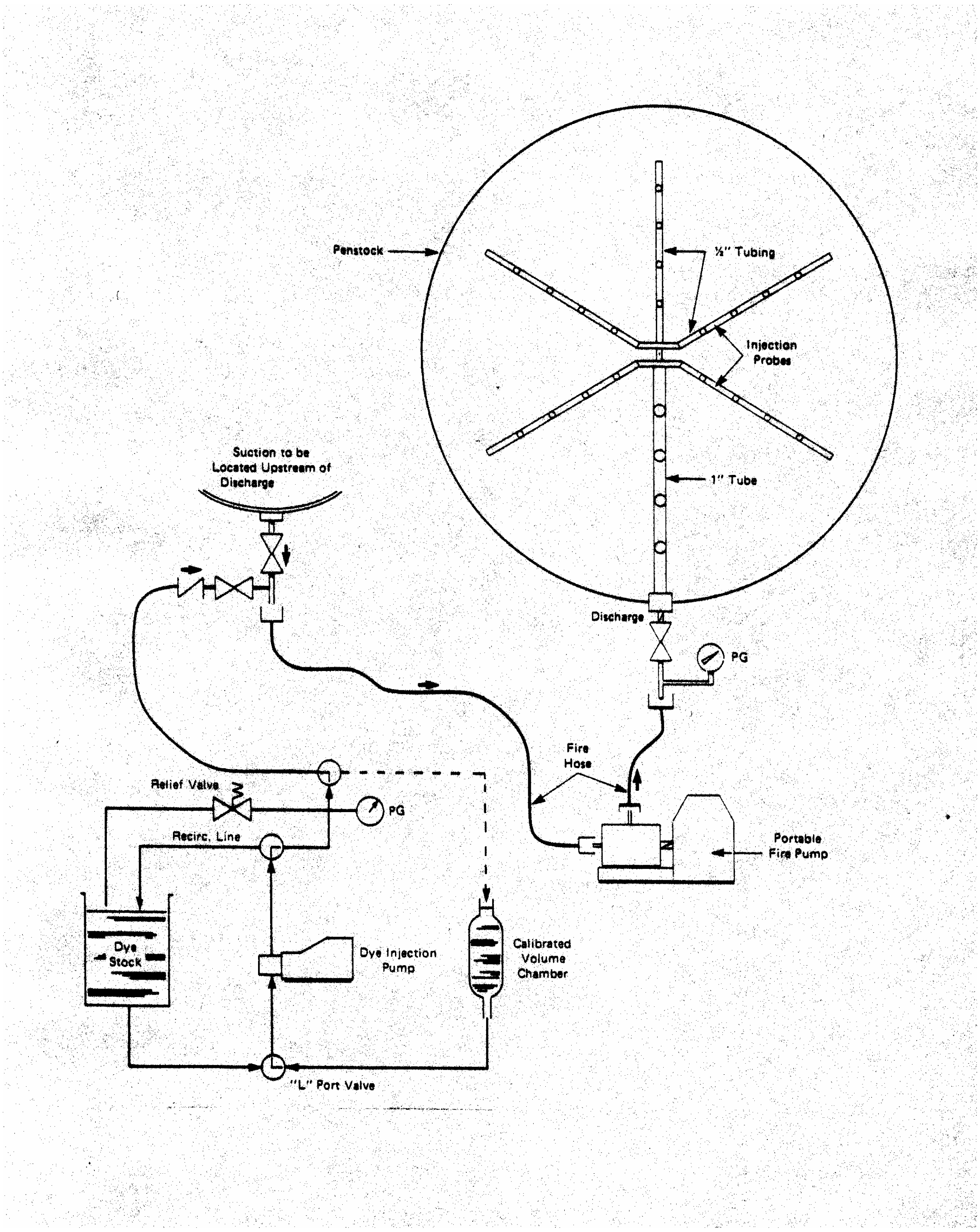

Figure 7
Arrangement of Multi-point Injection