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DESCRIPTION OF AN AIR-TIGHT GAS TRANSFER FLUME
AND AN EXPERIMENTAL PROGRAM FOR MASS TRANSFER
AT THE AIR-WATER INTERFACE

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MANAGEMENT PERSPECTIVE

The exchange of toxic organic contaminants across the air-water interface plays an important role in determining their fate in the environment. Without understanding the processes that control the exchange of chemicals across this interface it will be difficult to calibrate models to predict the direction or magnitude of the exchange in natural environments. The NWRI Gas Transfer Flume was designed specifically to examine wave mechanics, boundary layer turbulence and chemical parameters influencing the exchange of toxic organic chemicals across the air-water interface. This report outlines the physical and technical aspects of the construction and operation of this unique facility.

Dr. J. Lawrence
Director
Research and Applications Branch

PERSPECTIVE - GESTION

L'échange de contaminants organiques toxiques à travers l'interface air-eau joue un rôle important dans la détermination de leur devenir dans l'environnement. À défaut de comprendre les processus qui régissent l'échange des substances chimiques à travers cette interface, il est difficile d'étalonner des modèles pour prévoir la direction ou la grandeur de cet échange dans les milieux naturels. Le canal d'échanges gazeux de l'INRE a été spécialement conçu pour examiner la mécanique des vagues, la turbulence de la couche limite et les paramètres chimiques qui influent sur l'échange des composés organiques toxiques à travers l'interface air-eau. Le présent rapport décrit les aspects physiques et techniques de la construction et du fonctionnement de cette installation unique.

J. Lawrence
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Abstract

The NWRI Gas Transfer Flume is an air-tight wind wave tunnel designed to study wave and boundary layer mechanics influencing the mass transfer of toxic chemicals. The flume is 32.2 m long with a water depth of 0 to 25 cm. The wind is driven through a 0.76 m wide tunnel at 1 to 22.5 m/s by a 36 in. 25 hp vaneaxial fan and the water flow is recirculated at up to 0.6 m/s using a variable speed 15 hp vertical in line pump. Both the air and water can be filtered through charcoal filters before being expelled. Instrumentation is available at three different fetches to collect a variety of aerohydrodynamic and chemical data (e.g., capacitance wave gauge, laser displacement gauge, laser slope gauge, conical hot film anemometer). Aspects of the construction and operation of the NWRI Gas Transfer Flume are outlined.

RÉSUMÉ

Le canal d'échanges gazeux de l'INRE est un tunnel étanche conçu pour l'étude de la mécanique des vagues de vent et dues à la couche limite qui influe sur le transfert de masse des produits chimiques toxiques. Le canal mesure 32,2 m de longueur et de 0 à 25 cm de profondeur. Le vent est soufflé dans un tunnel de 0,76 m de largeur à une vitesse de 1 à 22,5 m/s par un ventilateur axial de 36 po et de 25 hp; l'eau est remise en circulation avec une vitesse pouvant atteindre 0,6 m/s à l'aide d'une pompe verticale en circuit de 15 hp à vitesse variable. L'eau et l'air peuvent être filtrés sur des filtres à charbon de bois avant d'être expulsés. Des instruments permettent de recueillir pour trois fetchs différents diverses données aérodynamiques et chimiques (par exemple, houlographe à capacité, indicateur de déplacement à laser, indicateur de pente à laser, anémomètre à film chaud conique). Les différents aspects de la construction et du fonctionnement du canal d'échanges gazeux de l'INRE sont résumés.

**DESCRIPTION OF AN AIR-TIGHT GAS TRANSFER FLUME
AND AN EXPERIMENTAL PROGRAM FOR THE DETERMINATION OF THE
MASS FLUX OF HIGH MOLECULAR WEIGHT ORGANIC SOLUTES
AT THE AIR-WATER INTERFACE**

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1.0 INTRODUCTION

Gas transfer at air-water interfaces is a complex process; it plays an important role in the geobiochemical cycling system. In particular, the exchange of gases such as oxygen and carbon dioxide is very important because both are involved in animal and plant life. Furthermore, the latter may influence the heat budget of the earth. High molecular weight organic compounds such as PCBs have impacts on the environment and human health. Sources and sinks of these compounds at the global scale as well as their flux rates at the air-water interface are not very well known.

Any mathematical mass balance model for any of these compounds in natural water bodies (lakes, ponds, etc.) requires accurate estimates of the mass transfer velocities across the air-water interface (Merzi and Donelan, 1987). The mass transfer (volatilization or absorption) rate of gaseous compounds is controlled by the water and/or gas phase. If most of the resistance occurs below the interface the transfer is liquid phase controlled; in the reverse case it is gas phase controlled. Gas transfer depends on the degree of turbulence intensity in the controlling phase. Consequently, a low-turbulence flume which permits controlled turbulence and chemical concentration measurements both in air and in water was constructed in order to conduct gas transfer experiments.

Similar flumes of this scale do exist at other research centres which are used to examine air-sea interaction problems: The I.M.S.T. Facility (Coantic and Favre, 1974), The Hamburg Wind Wave Facility (Hühnerfuss et al., 1976), The Stanford University Tunnel (Hsu, 1965). However, the Gas Transfer Flume (GTF) at Canada Centre for Inland Waters (CCIW) is unique, being air-tight and designed especially for gas transfer studies.

2.0 DESCRIPTION OF THE GAS TRANSFER FLUME

An air-tight (see Appendix 1) Gas Transfer Flume (GTF) was designed and constructed for mass (gas) transfer studies across the air-water interface as well as studies related to wave mechanics and boundary layer turbulence both in air and in water (Fig.1a-b).

The wind tunnel of the GTF may be operated either open ("ventilation" mode) or closed ("circulation" mode). In the ventilation mode air is drawn from the laboratory and after one circuit of the tunnel is returned (via charcoal filters and a roof vent) to the atmosphere. In this mode the air is essentially free of the chemicals being tested. In its present configuration the tunnel achieves centreline speeds up to 9 m/s in the ventilation mode. In the circulation mode the tunnel is tightly closed and the air circulates continuously. In this mode centreline wind speeds of up to 22.5 m/s are readily achievable.

The GTF provides mean water velocities up to 0.60 m/s with circulation possible in both directions. Paddle generated waves can be obtained in the flume by means of an electro-hydraulic wave maker.

The test section is 32.2 m long and 0.76 m wide; the water depth is designed to be up to 0.25 m and the height of the air duct is 0.60 m (Fig.2). The GTF is constructed of aluminum and the windows are made of normal glass. A vaneaxial direct drive fan (diameter = 36", corrosion proof steel) is driven by a 25 hp explosion proof variable speed motor (0-1800 rpm) (Fig.3). In the settling chamber (Fig.4) there is a honeycomb section (diameter = 1", length = 20 cm, thickness = 0.003", aluminum) to straighten the airflow and three fine mesh screens (16 wires/inch, thickness = 0.016", stainless steel) to dampen the

turbulence and increase the uniformity of the airflow. The airflow is guided at the corners of the GTF by circular corner elements ($r = 0.15$ m).

The water flow is obtained by means of a vertical in line pump which is driven by a 15 hp motor and controlled by a variable speed system (0-1800 rpm).

The gas transfer flume is equipped with a high efficiency HEPA filter (DOP 99.99 at a flowrate of $1.42 \text{ m}^3/\text{s}$) and a charcoal filter (same flow rate) in air (Fig.5) and a carbon filter (60 l/min) in the water (Fig.6). The HEPA filter is placed at the intake of the GTF. At the end of the experiment, air and water in the GTF can be discharged outside through these filters (the air to the atmosphere through the charcoal filter; the water to the storm drain through the carbon filter). The presence of these filters allows for the safe discharge of clean fluids to the environment.

There are three measuring stations in the GTF at different fetches. The fetches corresponding to these stations are $F_1 = 5.32$ m, $F_2 = 14.46$ m, $F_3 = 29.71$ m. The organization of a station is illustrated in Fig.7. At each station, there are glass windows on both sides of the test section (both in air and water). Each station is equipped with appropriate instrumentation to do aerohydrodynamic and chemical measurements (see section 3.0).

3.0 INSTRUMENTATION

The instruments which are available can be described in four groups: (1) instruments measuring aerodynamic and thermal characteristics in the air, (2) instruments measuring interfacial characteristics, (3) instruments measuring hydrodynamic and thermal characteristics in the water, (4)

instruments measuring the concentration of chemicals in the air and in the water.

3.1 MEASUREMENTS IN THE AIR

(1) An x-wire anemometer, fixed at $z = 15$ cm above water level at Station 2, will measure horizontal and vertical components of the turbulent air velocity. The data will be collected at a sampling frequency of 200 Hz and will be low-pass filtered at 100 Hz (Two channels are required in the Data Acquisition System (DAS) (See Section 5.0). The data will be used to compute the momentum flux.

(2) A cold wire thermometer, fixed at $z = 15$ cm above water level at Station 2, will measure temperature fluctuations. The data will be collected at a sampling rate of 200 Hz and will be low-pass filtered at 100 Hz (one channel is required in the DAS). The data will be used to compute the heat flux.

(3) Three Pitot static tubes will be mounted on the profilers (one on each profiler). Each Pitot static tube will measure the mean air speed at different fetches. The sampling rate is 1.5625 Hz (three channels are required in the DAS). The resulting air velocity profiles will be used to compute momentum flux.

(4) Three thermistors will be mounted on the profilers (one on each profiler). Each thermistor will measure the temperature of the air at different fetches. The sampling rate is 1.56525 Hz (three channels are required in the DAS). The resulting air temperature profiles will be used to compute the heat flux (with the help of the friction velocity obtained from the air velocity profiles or direct flux measurements).

(5) Three humidity sensors will be mounted on the profilers (one on each profiler). Each sensor will measure the relative humidity at different fetches. The sampling rate of 1.5625 Hz (three channels are required in the DAS). The resulting humidity profiles will be used to compute the humidity flux (with the help of the friction velocity obtained from the air velocity profiles or direct flux measurements).

At each station there is a profiler, which is remotely controlled via the DAS. Each profiler carries instruments which are described in (3), (4), (5), and the conical hotfilm which makes water velocity measurements (see Section 3.3). The profilers are located approximately 30 cm downstream of the capacitance wave gauges; they can be moved laterally as well. Note that fixed measurements will take place at the same alignment as the profilers (Fig.7).

3.2 MEASUREMENTS AT THE INTERFACE

(1) A capacitance wave gauge (CWG) is installed at each station. The diameter of the wire of the capacitance wave gauge is 0.2 mm. The sampling rate will be 50 Hz; the data will be low-pass filtered at 20 Hz (Three channels are required in the DAS). The data will be used for the determination of basic characteristics of the wave field.

(2) A laser displacement gauge (LDG) will be operational at one of the stations depending on the nature of the experiment. The LDG is an optical, non-intrusive system which will permit making wave measurements at high frequencies where surface tension force is the only restoring force. The set-up is illustrated in Fig.8. A 25 mW argon-ion laser beam which radiates at 488 nm enters the flume laterally through the glass window and is reflected upwards (towards the air-water interface). Commercial Fluorescein will be mixed in the water beforehand at a

concentration of 5.6 mg/l. (Total volume of water in the flume is approximately 10,000 l); absorption of Fluorescein takes place at 480 nm; it emits at 540 nm. A bright beam is observed in the water, whereas the refracted beam (through the air-water interface) in the air appears to be dark; There is a very sharp passage from bright to dark on the vertical laser beam in the flume. A photodiode array which has 512 elements (Reticon LC 310 C512), spaced 25.0×10^{-6} m (centre to centre) scans the interface vertically focusing the laser beam by a lens ($f = 100$ m). The field of view is taken as 10 cm; consequently the magnification ratio is $M = 10/(512 \times 0.0025) = 7.81$ and it follows that the spatial resolution is $0.0025 \times 7.81 = 0.01953$ cm. The width of the laser beam at the interface will be 1.41 mm = original width + divergence = $0.61 + \tan(1\text{mr}) \times 800$, where 1 milliradian is the divergence of the laser beam and 800 mm is the distance travelled by the laser beam before arriving at the air-water interface). To reduce this width, commercial optical elements may be used (Nelles Griot, 1989).

The scan starts from the first cell and ends at the last cell. Each cell sends a signal (0, if the intensity of the illumination is smaller than the present threshold value; 1, if not) to a controller which produces an analog signal that indicates the location where the sharp passage from the bright to the dark occurs; this is the place where the interface is located for this specific moment (Fig.9a-c) (Lin et al., 1978). The sampling rate will be 200 Hz (one channel is required in the DAS).

(3) A laser slope gauge (LSG) will be used to measure the slopes of the waves. This is again an optical, non-intrusive system (Kahma and Donelan, 1988). The laser beam is directed upwards through the water column and deflected at the surface in proportion to the local slope. The deflected beam is captured by a large Fresnel lens in the slope gauge above the tank (LSG

in Figure 7b), and focussed on a two-axis photodetector. The four electrical signals from the photodetector are recorded and, in combination, they yield two orthogonal slopes of the water surface - normally down tank and cross tank. The sampling rate will be 50 Hz; data will be low-pass filtered at 20 Hz (Four channels are required in the DAS).

3.3 MEASUREMENTS IN THE WATER

(1) A conical hot film anemometer (TSI) will be mounted on each profiler. It will measure turbulent water velocity fluctuations. The sampling rate will be 200 Hz and will be low-pass filtered at 100 Hz. (Three channels are required in the DAS) The data will be used to obtain drift profiles and to calculate the energy dissipation. (Merzi, Terray and Donelan, 1989).

(2) Same sensor as in (1) with constant-current electronics can be used to do water temperature measurements. The sampling rate will be 200 Hz and the data will be low-pass filtered at 100 Hz (three channels are required in the DAS).

3.4 CHEMICAL MEASUREMENTS

Water and air samples can be collected at all three stations. Downstream of each capacitance wave gauge there is one port reserved for water sampling (35 cm downstream) and one for air sampling (20 cm downstream). Air samples are collected by drawing air through a column of Tenax TA (0.6 x 8 cm) at a known flow rate (0-30 l/min) using a vacuum pump (Fig.10). An equal amount of filtered air can be returned to the GTF (at a port 20 cm behind the first) using a second pump to avoid pressure changes in the GTF. Water samples are collected by gravity flow, with the sample volume dependent on the characteristics of the experiment and the chemicals. Similarly chemical analysis

(including extraction, clean-up, fractionation and detection) are dependent on the concentrations and characteristics of the chemicals of interest. Sampling intervals will also be dependent on the characteristics of the experiment and chemicals.

3.5 INTRODUCTION OF CHEMICALS TO THE WATER

The chemicals of interest can be introduced into the water in two ways:

- (1) pumped directly into the water dissolved in a solvent such as acetone or
- (2) addition of "spiked" water from a separate tank.

The first method allows for accurate control of the initial concentrations, while the second method avoids artifacts created by adding hydrophobic compounds directly to the water. The chemicals are absorbed onto glass beads and packed into a stainless steel cylinder. Water is passed through the column and collected in a 2 m³ dilution tank. Once the preselected water volume has accumulated, the water in the tank is circulated through the bed of glass beads for a preselected period of time. The tank can then be drained by gravity into the GTF. If there is an excess of the chemical absorbed by the glass beads, then the concentration of the chemical in the water inside the tank will be approximately equal to its solubility. The water capacity of the GTF is 10 m³ so that if 1 m³ of water is drained into the GTF, then the initial concentration will be 10% of the solubility of the compound of interest.

4.0 EXPERIMENTAL PROCEDURE

The experiments will be conducted in two stages: aero-hydrodynamic measurements and chemical measurements. They will be conducted independently of each other, but under the same aero-hydrodynamic conditions. The reason for this is so as not to influence the concentrations of the compounds of interest by the presence of Fluorescein (which will be used in the LDG and LSG measurements).

4.1 AERO-HYDRODYNAMIC EXPERIMENTS

Each compound of interest will be tested at twelve different air speeds, (U (m/s) = 1.5, 2, 2.5, 3.5, 5, 6, 7.5, 8.5, 10, 12.5, 15, 17.5). At each of these speeds, at each station, profile measurements will be conducted. Profile measurements consist of air speed, relative humidity, air temperature and water velocity. These four instruments are mounted on the profiler as shown in Fig.7b. There will be 20 points (logarithmically ordered).

There will be fixed level measurements using an X-film probe and cold wire (see Section 3.1) at the same alignment (17 cm laterally shifted) as the profiler at $z = 15$ cm above the air-water interface.

OWG measurements will take place during each repetition of the same run at the same station whereas LDG and LSG instruments will be shifted to other stations each time.

The duration of each physical experiment is about two minutes (see Section 5.0).

4.2 CHEMICAL EXPERIMENTS

A series of compounds which represent a range in the Henry's Law Constant will be selected such that some are liquid phase controlled (e.g. CO_2) and some are gas phase controlled (e.g.

mirex) and some lie between these extremes (e.g. PCBs). The best approach to conducting the experiments will be dependent on the properties of the chemicals of interest. The following discussion describes two approaches using chemical measurements in the water.

The Henry's Law constant indicates the direction of transfer of chemicals but does not predict the flux (moles/m²h) or the rate of volatilization (h⁻¹). The two-film (two resistance) theory is a widely used model to describe volatilization but other models do exist (Merzi and Donelan, 1987). The overall mass transfer coefficient, K_{o1}(m/h) is often expressed as:

$$1/K_{o1} = 1/K_l + (RT)/(HK_g) \quad (1)$$

where K_l and K_g are the mass transfer coefficients referring to the liquid or the gas phase, R is the gas constant (82x10⁻⁶ atm m³/(mol K⁰)) and H is Henry's Law Constant (atm m³/mol) and T is the temperature (K⁰). This is simply an application of Fick's first law of diffusion;

$$N = K_{o1} \partial C \quad (2)$$

where N is the flux of the chemical (mol/m² h) and ∂C is the concentration gradient (mol/m³). The concentration in the air can also be expressed as C_a = P/H, where P is the vapour pressure (Pa) such that eq.(2) becomes

$$N = K_{o1} (C_w - P/H) \quad (3)$$

The change in concentration in the water can be written as;

$$dC_w/dt = -K_{o1}(C_w - C_a)/d = -K_{o1}(C_w - P/H)/d \quad (4)$$

where d is depth of water. If P is zero, ("ventilation" mode) integrating (4) over time 0 to t, one obtains,

$$C_w = C_{w0} \exp(-K_{o1} t/d) \quad (5)$$

where C_{w0} is the initial concentration in the water. The half-life in the water is then:

$$t_{1/2} = 0.693 d/K_{o1} \quad (6)$$

The mass transfer coefficient for a given chemical can therefore be determined by measuring the decrease in the concentration of the chemical in water with time. The slope of the $\log (C_w/C_{w0})$ vs t relationship is K_{o1}/d .

An alternative method of determining the mass transfer velocity is to have a continuous input of the chemicals of interest into the water while in the "ventilate" mode. When the entire system is at equilibrium,

$$\frac{I}{A} = N = K_{o1} \delta C \quad (7)$$

where I is the rate of input (mol/h) and A is the water surface area (m^2). Because the concentration of the chemical in the air is approximately zero relative to the concentration in the water, the concentration gradient (δC) is approximately equal to the concentration in the water (C_w), such that,

$$K_{o1} = \frac{I}{AC_w} \quad (8)$$

Therefore, the concentration of the chemical in the water needs to be measured only after the system has reached equilibrium.

5.0 DATA ACQUISITION SYSTEM

The data acquisition system (DAS) uses an IBM PC AT and two Data Translation 2801 boards and a custom interface board. The maximum data throughput of this configuration is approximately 16000 samples per second on a single channel. With 32 channels of acquisition, the maximum sampling rate for each channel is 400 samples per second. The internal memory of the IBM PC AT will be used for temporary storage of the data as it is acquired. This allows approximately 250,000 samples of the data to be stored in 500 kb of memory. The number (1-16) of channels on each board of the data acquisition system and their individual sampling rates are flexible.

The sampling rate of any channel is variable between 400 samples per second and its division by a multiple of 2 (the minimum sampling rate of any channel is around 1 sample per minute). The sampling rate for every channel in one board is the same, but the sampling rates of the two boards may be different. Channel numbers on each board are consecutive starting with the first. The duration of the recording is adjustable in terms of seconds. The DAS starts the controller of the profiler system at the beginning of the recording.

The data are recorded in cross-channel sequences in binary form. The software of the Data acquisition system (DAS88 2nd version) allows the sorting of each channel as a separate file in ASCII code.

6.0 POWER SUPPLY AND CONTROL ROOM

The necessary power for the motor of the fan goes to the "fan control cabin", which houses the control system and the variable speed system of the fan (Fig.11). The calibration curve which relates the frequency of the power delivered to the fan and the

air speed (for different water depths) is attached to the fan control cabin (Fig.11). The variable speed system of the water pump is next to the water pump. The calibration curve of the water pump is next to the water pump on the flume. There are three 115 volts (15 amp) plugs at the south side of the GTF (suspended from the ceiling). The control room receives its power from the 115 volts (15 amp) plug attached to the wall on the north side of the GTF.

7.0 FURTHER MODIFICATIONS AND DEVELOPMENTS

The GTF is working satisfactorily as it is now, but some further modifications and developments concerning both the flume itself and the instrumentation are necessary in order to meet the requirements imposed by new targets and specifications which will lead to more precise and specific data.

7.1. GAS TRANSFER FLUME

(i) Static pressure distribution of the GTF should be determined for different wind speeds. The points of rapid pressure change are shown in the following conceptual drawing (Fig.12). The wind speeds to be tested are $U = 2.5 \text{ m/s}$ to $U = 22.5 \text{ m/s}$ with 2.5 m/s increments.

(ii) If waves are breaking there is a high probability that sprays will be conveyed to the return duct and deposited there. There should be some mechanism which will trap all the spray droplets before they pass the third corner. This could be a screen placed in the diffuser just at the downstream end of the flume. The bottom level of the diffuser is below the stillwater level, so the water (accumulated as a result of sprays) has to be pumped to the tail box.

7.2. INSTRUMENTATION

- (i) The already existing wave follower system (Donelan, Anctil and Doering, 1990) might be adapted to the GTF to do aerodynamic and hydrodynamic measurements with respect to wave motion.
- (ii) A laser Doppler velocimeter (LDV) should be provided to measure turbulent water velocities (in addition to the already available conical hotfilm).
- (iii) A CO_2 analyzer (Licor) should be provided for the measurements of this water phase controlled compound.
- (iv) Many researchers find bubbles responsible for the enhanced gas transfer where wave breaking starts to occur. A bubble measuring device should be incorporated into the GTF in order to test bubble-originated gas transfer assumptions (Hsu and Wu, 1984; Broecker and Siems, 1984; Jähne, Wais and Barabas, 1984; Memery and Merlivat, 1984).
- (v) There are certain disadvantages to making wave measurements to be analyzed only in the frequency domain. Imaging slope gauges (ISG) (Jähne, 1989) may be adapted to the GTF in order to obtain wave number spectra at large wave numbers.

APPENDIX 1

ABOUT THE AIR-TIGHTNESS OF GTF AND BEYOND

The air leakage rate of the GTF has been estimated to be 3% per day. According to the gas law,

$$(P_1 V_1) / (n_1 R T_1) = (P_2 V_2) / (n_2 R T_2) \quad (1)$$

where P is pressure, V is volume, n is number of molecules, R is the gas constant and T is temperature. Assuming that T and V are constant, eq.(1) becomes,

$$P_1/P_2 = n_1/n_2 \quad (2)$$

which means that change of pressure in the GTF can be related to the change of the amount of air. Experiments have been done to estimate this value. The GTF was pressurized to 15 cm of water (relative to the atmosphere) and then pressure was measured in the GTF as a function of time (See Fig.13). The leakage rate was calculated as the slope of the pressure vs time curve divided by the initial total pressure. When the flume was commissioned this was found to be 0.00125/hr. This is equal to approximately 3% per day (note that this value is obtained by using 15 cm relative pressure; this is twice the maximum relative pressure which will occur in the GTF).

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FIGURES

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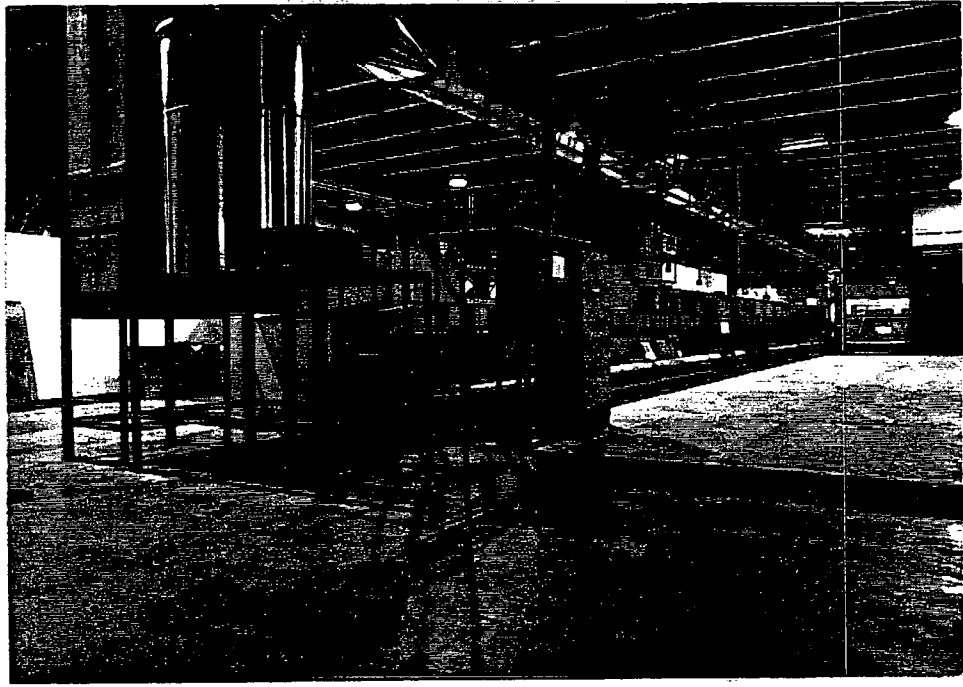


Fig. 1a. General view of the Gas Transfer Flume.

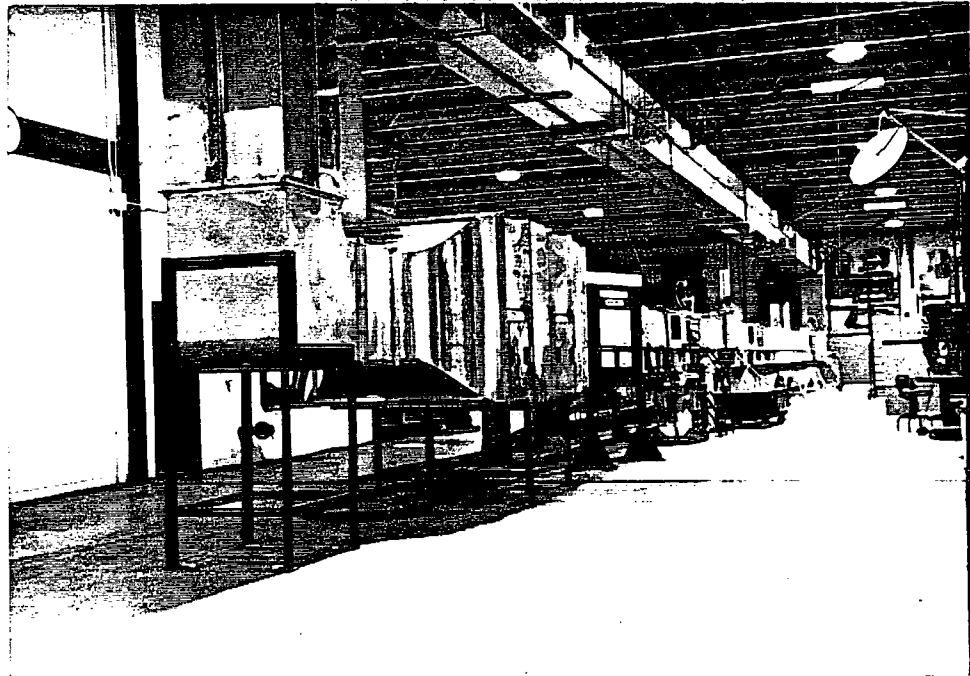


Fig. 1b. General view of the Gas Transfer Flume.

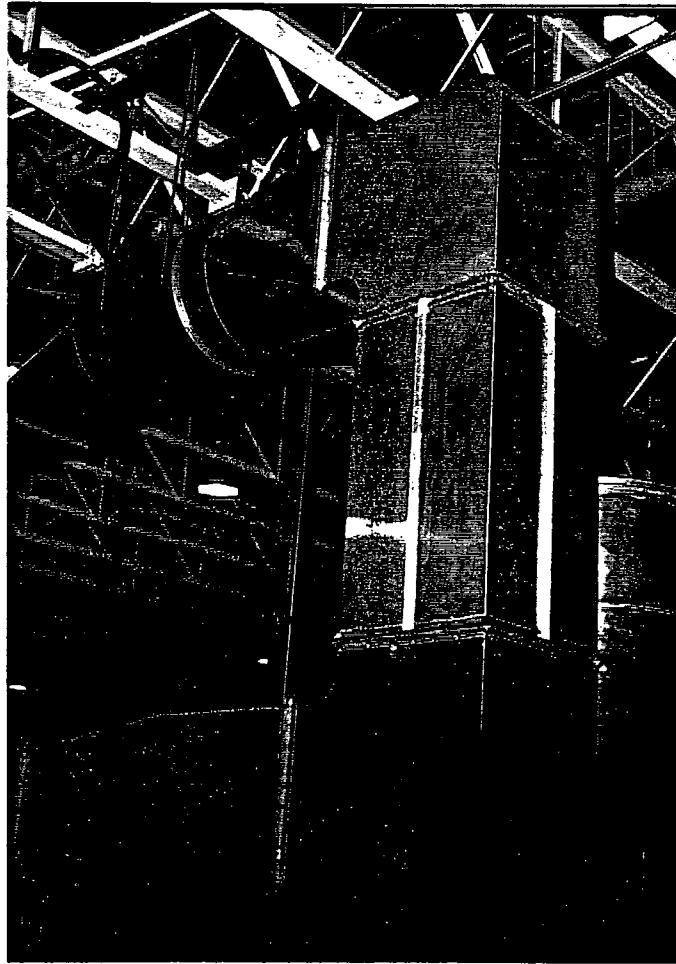


Fig. 3. The 36 in. vaneaxial fan.

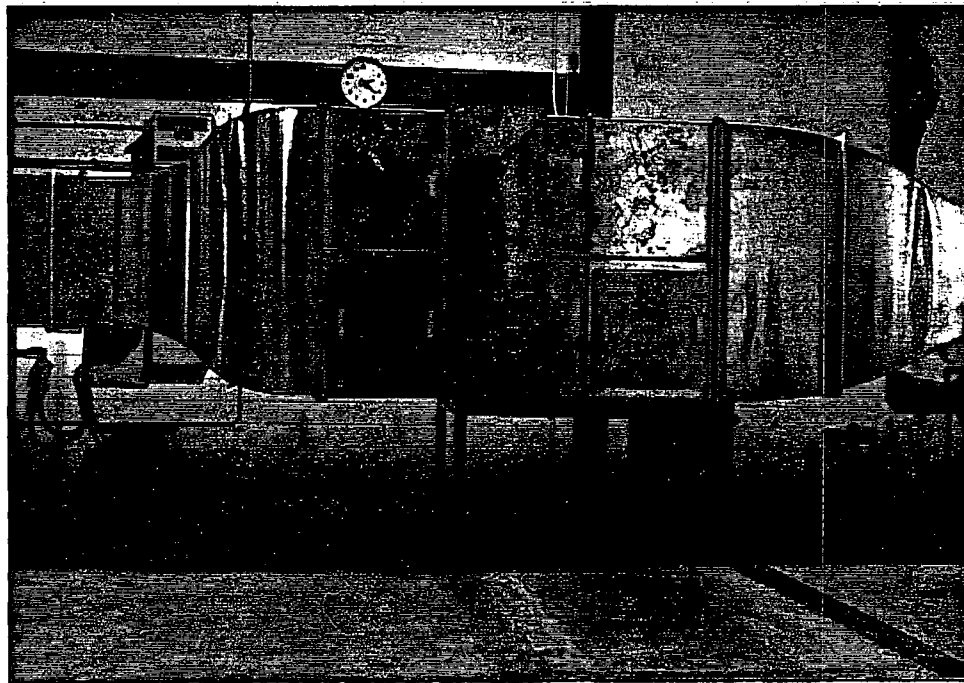


Fig. 4. The settling chamber.



Fig. 5. HEPA and charcoal filters for purifying air.

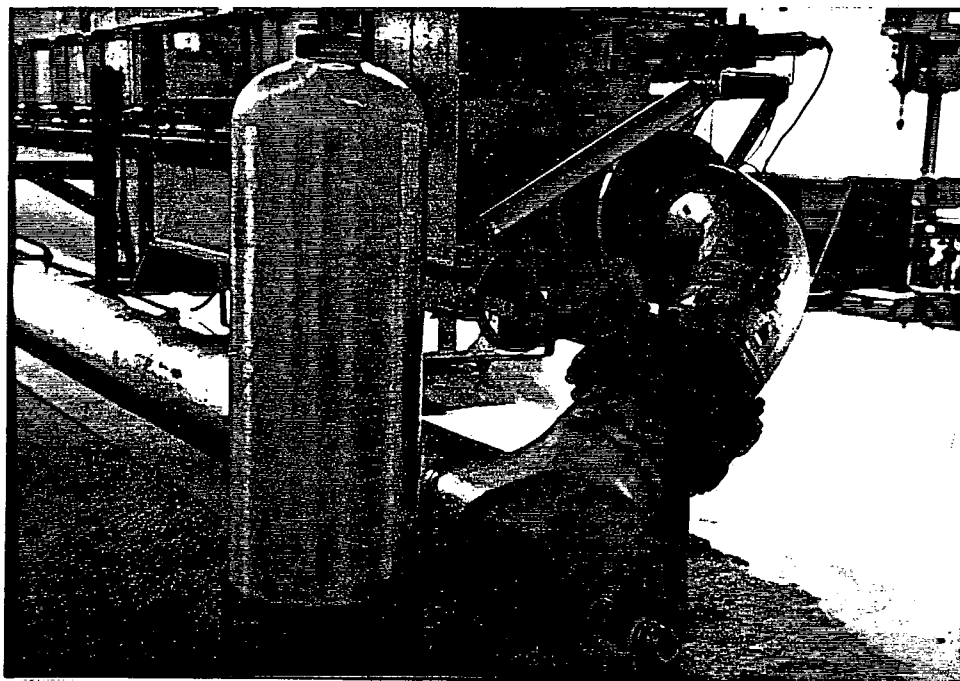


Fig. 6. Charcoal filters for purifying water.

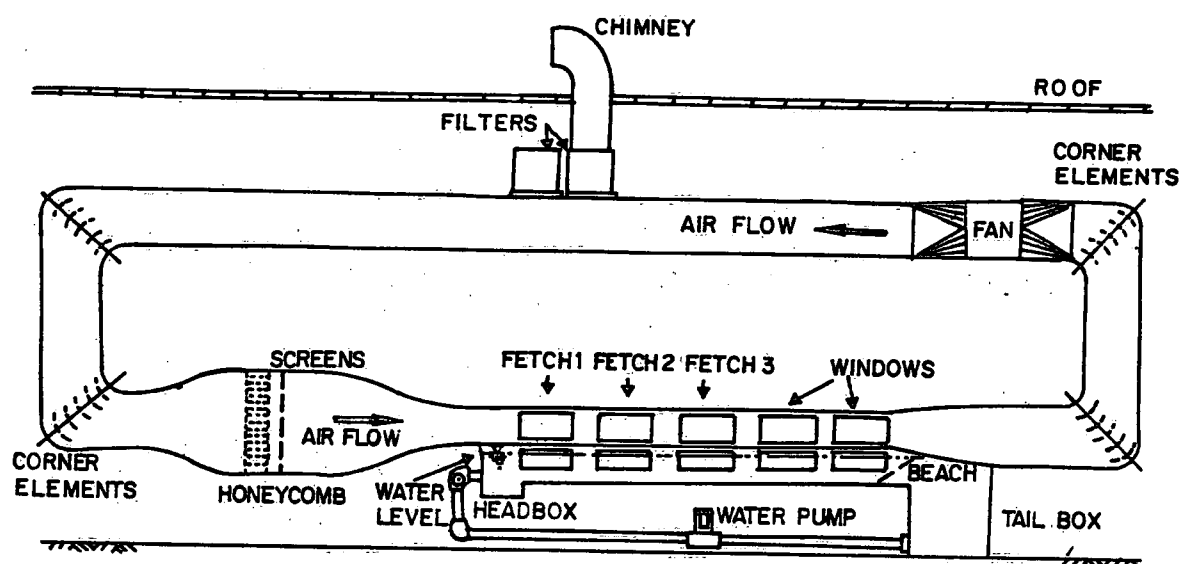


Fig.7a Location of measurement stations in the Gas Transfer Flume. (Not to scale)

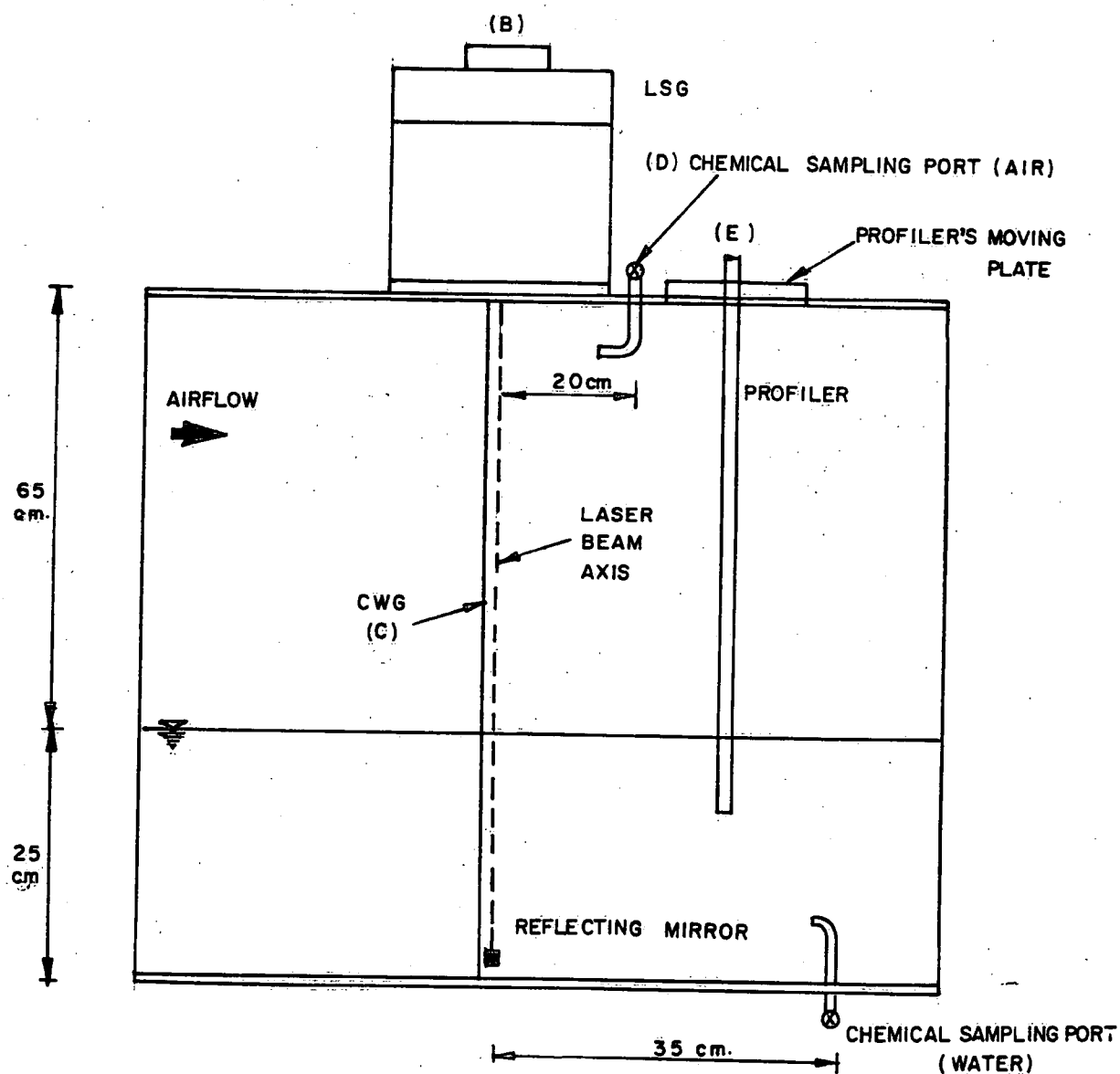
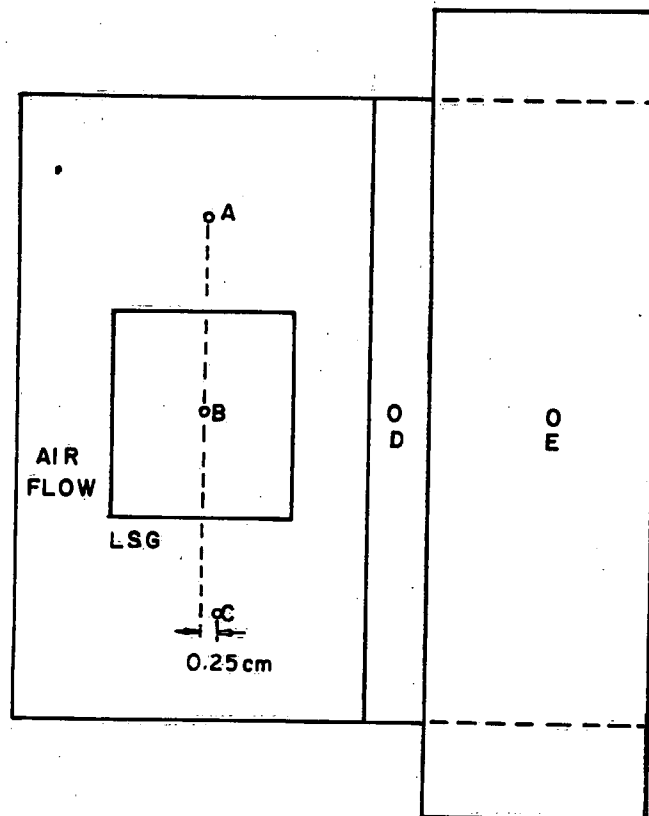


Fig. 7b. The organization of the measurement stations.



- A FIXED LEVEL MEASUREMENTS AXIS
- B LASER BEAM AXIS
- C CWG AXIS
- D CHEMICAL SAMPLING PORT
- E PROFILER'S AXIS

Fig. 7c. Top view of a measurement station.

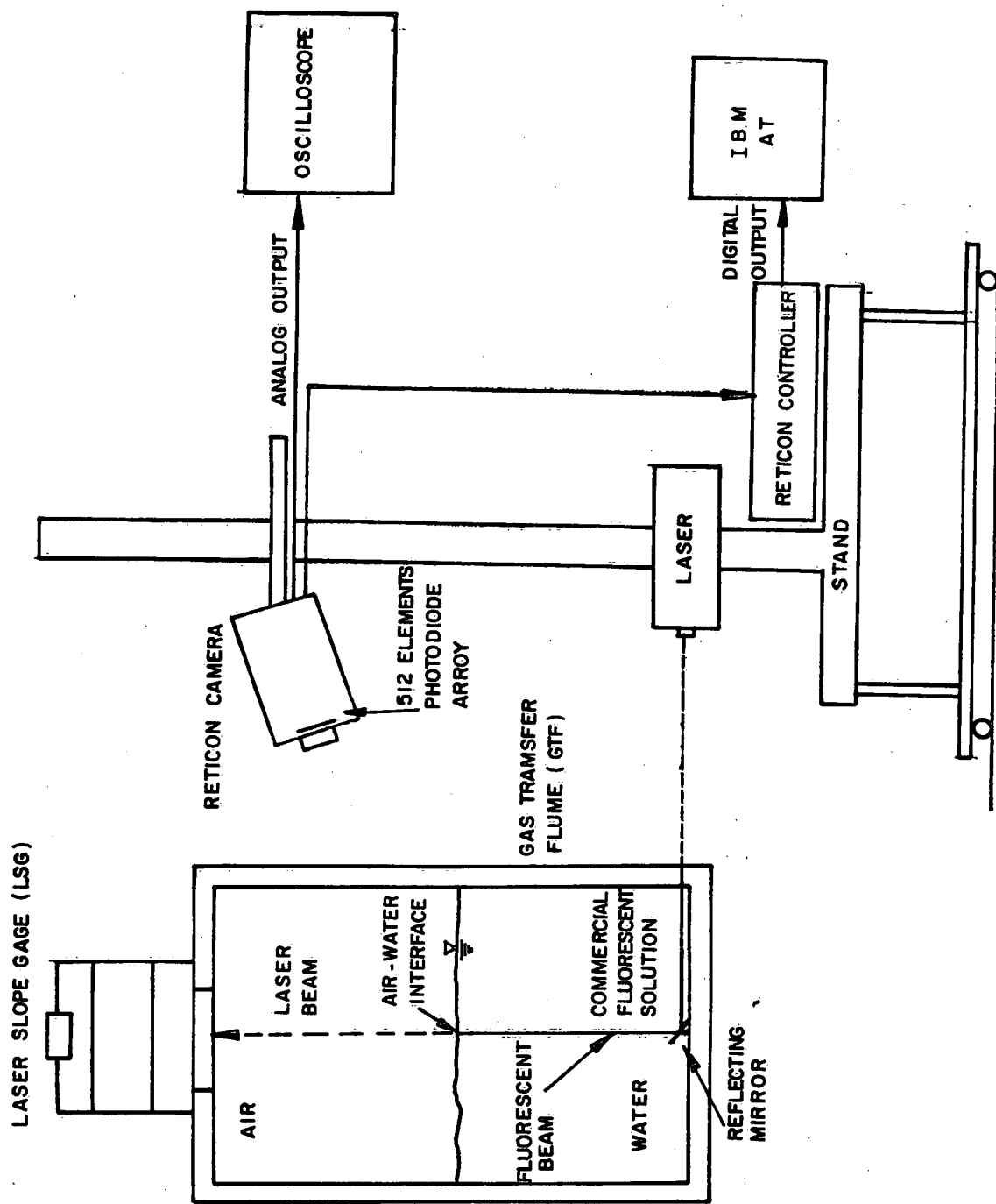


Fig. 8. Set-up of the laser displacement gage.

Fig. 9a. Illustration of the "bright" and "dark" parts of the laser beam.

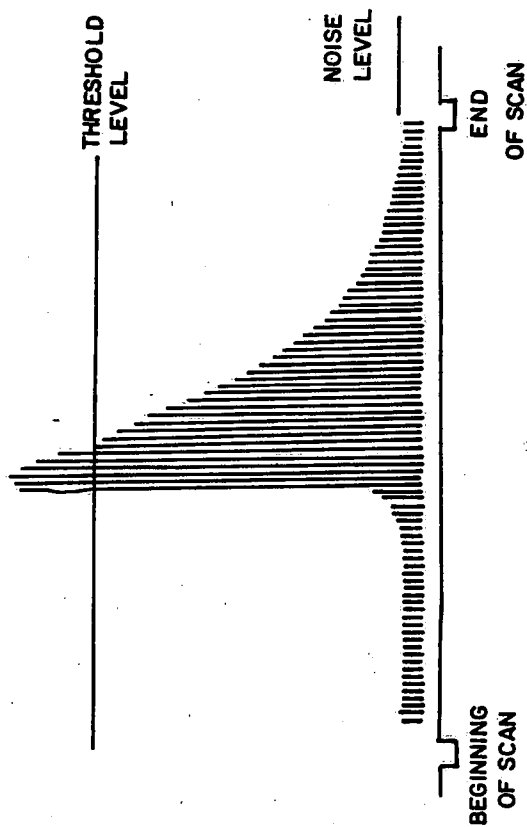
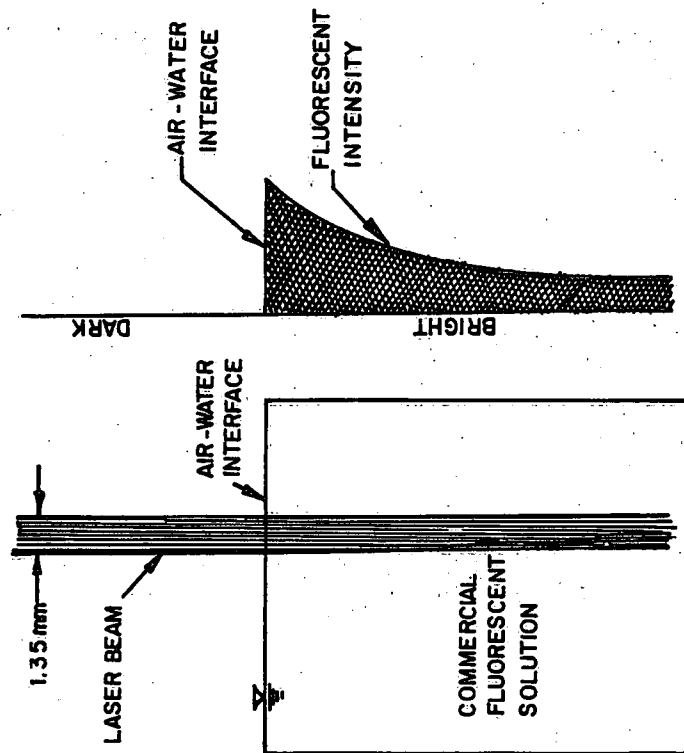


Fig. 9b. Analog output on the scope.



Fig. 9c. "Bright" and "dark" pulses.

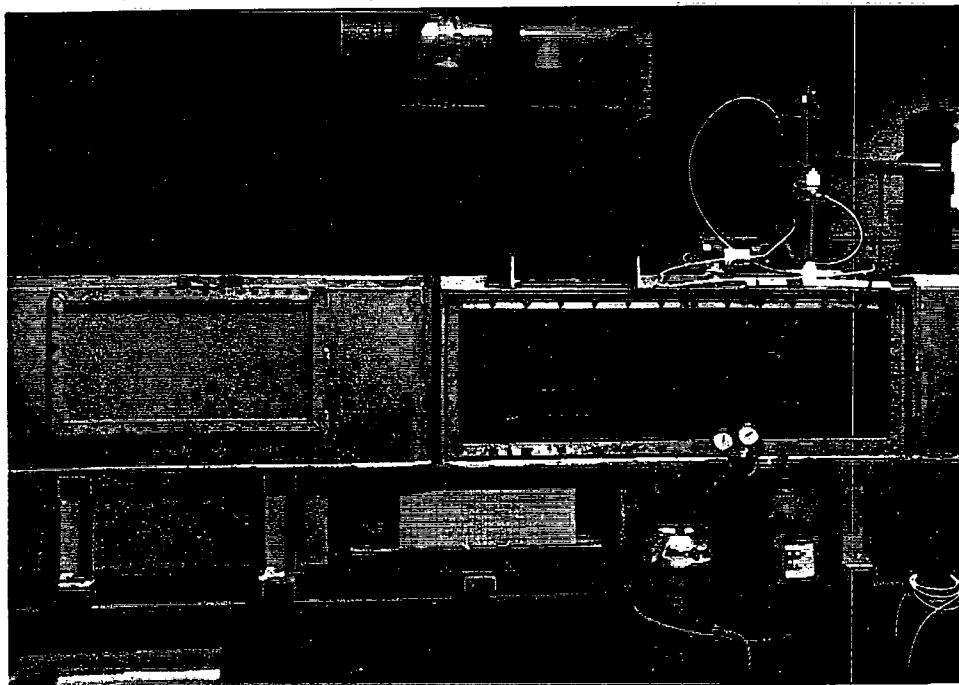


Fig. 10. Set-up for measurement of chemicals in the Gas transfer Flume.

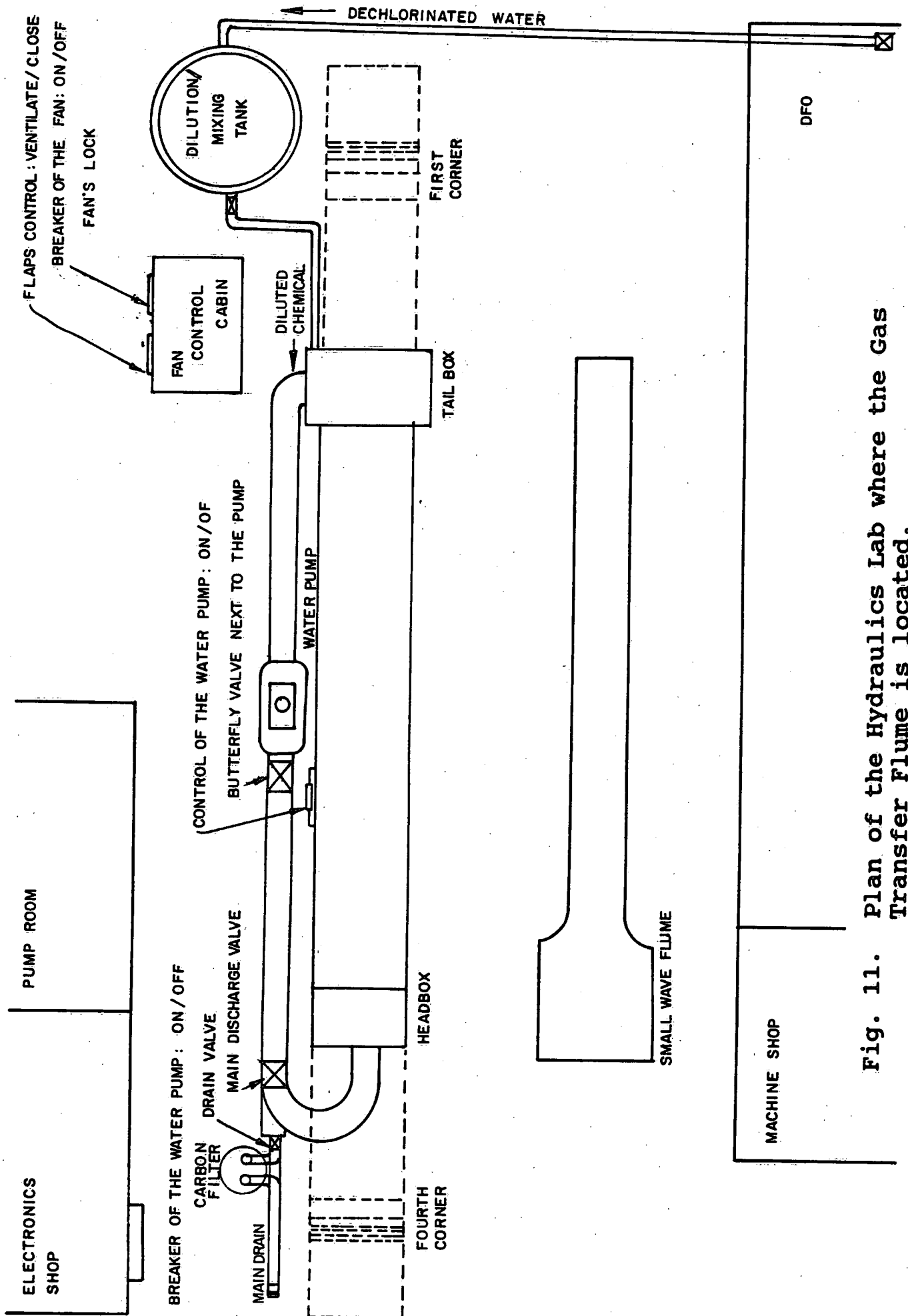


Fig. 11. Plan of the Hydraulics Lab where the Gas Transfer Flume is located.

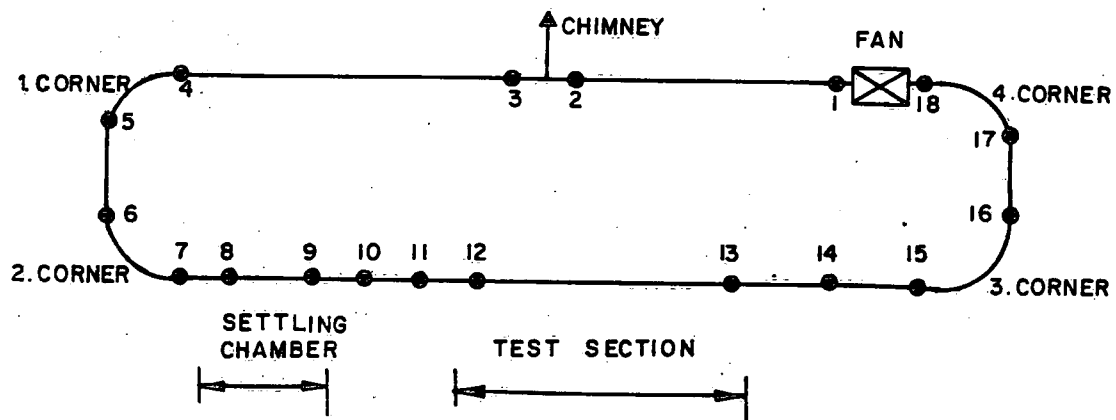


Fig. 12. Singular points of the Gas Transfer Flume.

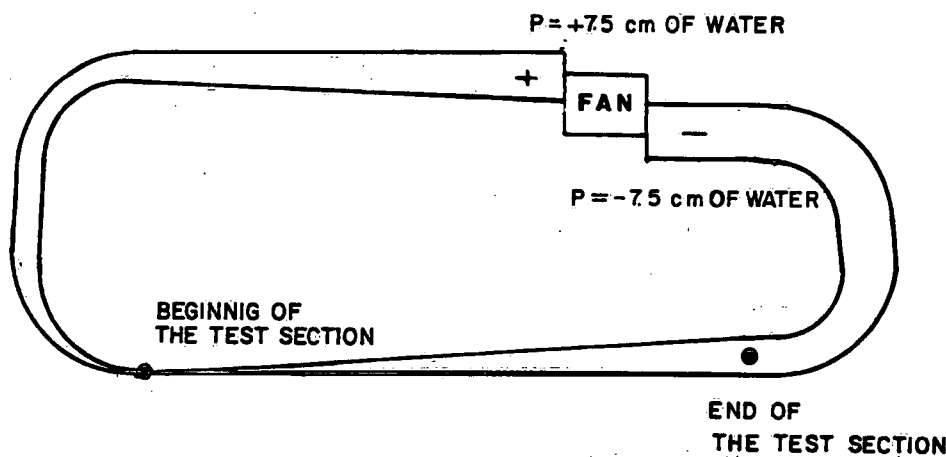


Fig. 13. Hypothetical pressure distribution in the Gas Transfer Flume.

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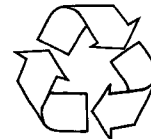
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