HEAVY WATER PLANTS
AND THEIR FLOW MEASUREMENT

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ABSTRACT

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The present generation of Canadian heavy water plants are limited in operability by the inadequacy of available flow measuring equipment.

This report summarizes the flow measurement devices currently in use, and their limitations, then proceeds to investigate other measurement devices which are being actively developed for use in heavy water plants. It concludes with a short survey of devices or techniques which have not been seriously considered to date, but which hold promise of commercial success, and suggests further investigation to develop one of these devices for practical application in heavy water plants. To clearly establish the importance of flow measurement and control in heavy water plants, the details on flow measurement are preceded by introductory chapters on heavy water and its production.

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TABLE OF CONTENTS. Page No.

NOMENCLATURE

a	throat area
A	pipe area
B	flux density
C	coefficient of discharge
d	diameter
D	pipe diameter
e	Electro-motive-force (e.m.f.)
F	force
g	gravitational acceleration
G	gas flow rate (molar)
K	equilibrium constant
L	liquid flow rate (molar)
M	mass flow rate
n	frequency
p	pressure
q	volumetric flow rate
R	molecular weight gas constant
Re	Reynold's number
S	Strouhal number
T	absolute temperature
V	velocity
x	mole fraction of deuterium in x (liquid) phase
y	mole fraction of deuterium in y (gas) phase
Y	expansion factor

Z	compressibility factor
α	Separation factor
β	diameter ratio
γ	ratio of principle specific heats of an ideal gas
δ	distance
ρ	density

Subscripts

c	cold tower
h	hot tower

LIST OF FIGURES

Figures

LIST OF TABLES

Tables

x

INTRODUCTION

Canada's nuclear power program is based on the CANDU reactor. The term CANDU is an acronym of Canada-Deuterium-Uranium, indicating that the reactor is fueled by uranium and moderated and cooled by heavy water (deuterium oxide). The uranium fuel is used in it's natural form, i.e. without any enrichment to increase the proportion of the fissile isotope, uranium - 235. The naturally occurring proportions of uranium are uranium 235 - 0.71%

uranium 238 - balance

Without the need for enrichment of the uranium, fuel manufacture for CANDU reactors involves basically mining, refining and manufacturing of fuel elements, and requires only moderate investment in technological development and in manufacturing facilities.

However, the use of natural uranium fuel carries with it certain limitations.

To maintain a fissile chain reaction, very few of the neutrons produced by fission may be wasted, and this necessitates the use of a very efficient moderating material, heavy water.

Production of heavy water, like production of enriched uranium, is an isotope separation process, although differences in properties between heavy water and ordinary (light) water are much greater than those between uranium 235 and uranium 238. Separation of heavy water is therefore considerably easier and less expensive than separation of uranium 235.

Many processes have been investigated for separation of heavy water, but almost all of the worlds production has been produced by the Girdler-Sulphide process, and this process is used in all of Canada's commercial plants.

Although more than 20 years have elapsed since the first plant utilizing this process came into operation in the United States, the flow measurement techniques used are still not adequate by themselves to enable the gas and liquid process flow rates to be set at the optimum values for maximum production of heavy water.

The objective of this report is to evaluate a cross section of flow measurement devices or techniques which appear to be potentially suitable for use in heavy water plants, and to recommend a program for further development of those devices which have the greatest potential.

Chapter 1 presents basic information on heavy water, its use as a nuclear moderator, and on its properties which make it suitable for this use, and which are the basis for its separation from ordinary (light) water.

Chapter 2 investigates the production of heavy water. Those processes which have been seriously considered for commercial application are summarized briefly, before proceeding to survey the history of commercial production in North America.

Chapter 3 describes the fundamentals of the Girdler-Sulphide process, which has been used for almost all the commercial production of heavy water in North America and for all of the commercial plants in Canada. The process description concentrates on explaining those parameters which affect the yield of heavy water from the plant, in particular the accurate balancing of the liquid and gas flow rates.

Chapter 4 of the report deals specifically with flow measurement. The techniques currently in use are evaluated followed by a survey of techniques which are already being investigated by Canada's heavy water industry, and concluding by a survey of other devices which appear to fulfil the basic requirements for heavy water plant use.

The conclusion selects from the surveyed devices those which offer the greatest potential for heavy water plant application and outlines the development which will be necessary for them to be used in heavy water plants.

CHAPTER 1 - HEAVY WATER

1.1 Nuclear Properties

Deuterium is one of three known isotopes of hydrogen. Natural water contains mainly the isotope of atomic weight 1.0, (protium or hydrogen), with a very small proportion of the isotope with atomic weight 2.0, (deuterium). The third isotope (tritium) of atomic weight 3.0, is radio-active and occurs naturally only in extremely small concentrations. The approximate naturally occurring concentrations are:

protium	-	99.985%
deuterium	-	0.015%
tritium	-	0

Chemically the isotopes have almost identical properties. However the presence of one neutron in the nucleus of a deuterium atom in addition to the single proton imparts significant differences in the nuclear properties of hydrogen and deuterium.

Heavy water is used solely as a moderating material for nuclear reactors, no other use has yet been found for this material. The function of a moderator is to decelerate the neutrons produced in the fission process of a nuclear reactor core until they are travelling in the speed range (thermal range) most likely to cause fission in the event of a collision with a fissile nucleus. The light elements, which most closely approximate to the neutron itself in weight, perform this function best.

Hydrogen, being the lightest of all the elements, is the most efficient in slowing down neutrons to the thermal range. However, the protium isotope, which predominates in nature, has a very high neutron capture cross-section, so that the neutrons which are available to cause fission and perpetuate the nuclear chain reaction, are very readily absorbed by the hydrogen. Deuterium, which already has a neutron in its nucleus, has an extremely small capture cross-section and thus is a more efficient moderating element than ordinary hydrogen.

Deuterium is used in the form of water because this is a most convenient form for handling.

The actual efficiency for a moderator is measured by a parameter called the moderating ratio,(1) which is a measure of its moderating capacity compared to its absorption capacity.

Other good moderator materials are ordinary (light) water, beryllium, and graphite.

The moderating ratios of these moderating materials are:

light water	- 60
beryllium	- 150
graphite	- 170
heavy water	- 2000

The use of heavy water as a moderator in Canadian nuclear power plants has made possible a number of advantages. One of these is the use of natural uranium fuel, as opposed to the enriched fuel that has to be used in other major nuclear power systems.

Significant economies thus accrue in the fuel cycle, by eliminating the high cost of uranium enrichment and by making maximum utilization of the uranium.

1.2 Physical Properties

The various methods that have been used for the separation of heavy water have been based on the differences in physical properties between the two isotopes, since chemically there is negligible difference.

These different physical properties between the heavy and light isotopes of hydrogen result from the differences in about mass of the two isotopes due to the additional neutron in the nucleus of deuterium. (1) The difference in physical properties is large for pure hydrogen since this mass ratio is two to one, but the difference becomes less for compounds of hydrogen since the mass ratio becomes less as the proportion of other elements in the compounds increases. Thus the mass ratio of heavy water to light water is 20 to 18 and differences in physical properties tend to approximate to this ratio. The most important physical properties of heavy water and light water are tabulated below.

Table 1. Physical Properties of Heavy Water & Light Water

	Heavy Water	Light Water
Molecular Weight	20	18
Density (Max).	1.1073	1.00
Boiling Point	101.42°C	100°C
Freezing Point	3.82°C	0°C

Separation of heavy from light water is therefore not as simple as the separation of deuterium from hydrogen, but this disadvantage is more than offset by the ease and low cost of obtaining supplies of water, ease of handling, storage, etc.

1.3 Equilibrium Constant

In any separation process, the concentration of each of the components can be expressed in terms of an equilibrium constant. The constant, and consequently the relative proportions of the components, normally varies with temperature and/or pressure.

The GS (Girdler-Sulphide) process accounts for most of the world's production of heavy water. It is based on the fact that, in a liquid system involving hydrogen sulphide and water, four components exist, namely light water H_2O, deuterated water HDO, hydrogen sulphide H_2S, and deuterated hydrogen sulphide HDS.

These are interrelated by the reaction:

$$H_2O + HDS \quad HDO + H_2S \qquad (1)$$

The equilibrium constant [2] for this reaction is:

$$K = \frac{[HDO]}{[H_2O]} \quad \frac{[H_2S]}{[HDS]} \qquad (2)$$

This equilibrium constant varies with temperature. At low temperature the reaction is displaced further in the direction to HDO $+ H_2S$ than it is at high temperature. This temperature effect is the basis for the use of H_2S as a separating agent for deuterated water.

At low deuterium concentration, the reaction results only in separation of HDO from H_2O. At high concentration the same reaction kinetics apply to separate D_2O from HDO.

However, a simple vacuum distillation process has been found most economic at these higher concentrations.

1.4 Separation Factor

The separation factor [3] for an extraction process, is defined by the equation $\alpha = \frac{x}{y} \frac{[1-y]}{[1-x]}$ (3)

Where x is the deuterium concentration in one of the reaction components or phases

, and y is the deuterium concentration in the other component of phase.

In the GS process x is the concentration in the water (liquid) phase, and y is the concentration in the hydrogen sulphide (gas) phase.

The GS process is used only at low concentrations and thus equation 3 approximates to $\alpha \doteq \frac{x}{y}$ (4)

This separation factor is equal to the equilibrium coefficient where the two components are immiscible and contain the same number of exchangeable atoms. In the hydrogen sulphide- water exchange process, where one component is soluble in the other, the separation factor differs slightly from the equilibrium coefficient.

This difference in the value of the separation factor at different temperatures can be used to effect a separation of deuterium by alternately contacting the two components at low temperatures to enrich one component, in deuterium, entracting a portion of this component as product, and then contacting the two components at a higher temperature to reverse the reaction and re-enrich the depleted component.

The remainder of the component which was enriched first to provide a product steam is discharged as waste at a concentration lower than that at which it was introduced into the process. The quantity of deuterium which can be extracted from the feed stream by such contacting is fixed by the difference in the value of the separation factor at the two temperatures of operation.

The temperatures of operation of the GS process are 30° C and 130° C and the values of the separation factor (4) at these temperatures are:

$$\alpha_{30} = 2.2 \quad \text{and} \quad \alpha_{130} = 1.75$$

The net recovery of deuterium is given by:

$$\frac{\alpha_{30} - \alpha_{130}}{\alpha_{30}} = \frac{2.2 - 1.75}{2.2} = 0.2 \qquad (5)$$

Thus no more than 20% of the deuterium in the feed water can be extracted.

CHAPTER 2 - HEAVY WATER PRODUCTION

2.1 Summary of Commercially Attractive Processes

Although this report will deal more with the GS process of extracting heavy water, other processes which have been used commercially or appear to have some potential, are listed below with their respective advantages and disadvantages.

TABLE 2

Methods of Separation of Heavy Water or Heavy Hydrogen

Method	Advantages	Disadvantages
Distillation of hydrogen (2)	Large difference in volatility of H vs. D, hence ease of separation	Involves large-scale distillation of liquid hydrogen for which commercial technology is not fully developed; limited commercial sources of hydrogen gas.
Fractional diffusion, hydrogen gas (2)	Good separation factor; simple equipment	High energy requirement and large investment in gas compressors
Electrolysis of water (2)	Good separation factor	Very high electric energy consumption
Distillation of water (2)	Simple equipment and operation	High thermal energy requirement and low separation factor
Gas-liquid exchange processes		
H_2S-H_2O, dual temperature(2)(3)(4) (hereafter called the GS process)	Good separation factor with moderate energy and equipment requirements; no catalyst	Toxicity of H_2S; corrosive nature of the H_2S-H_2O system
H_2-NH_3, dual temperature (2)	Good separation factor; reasonalbe equipment and energy requirement; simple homogeneous catalyst	Requires secondary source of D since NH_3 supply is limited;
H_2-NH_3, single temperature (3)(4)	Good separation factor; smaller equipment volume than dual temperature process	Requires secondary source of D, process more complex than dual temperature due to additional facilities required. Energy requirements are also slightly larger.
H_2-H_2O, dual temperature (3)	Good separation factor, lower volume requirements process, liquid phase reaction	Catalyst required which can be operated at the high process pressures without poisoning

Method	Advantages	Disadvantages
H_2-H_2O, single temperature (2)(3)(4)	Good separation factor; atmospheric pressure operation	Vapor-phase exchange reaction over catalyst; applicable only where supply of pure hydrogen is available (as at Trail, B.C.)
H_2-amine (5)	Some advantages as H_2-NH_3 processes, but can select amine with lower vapour pressure and faster reaction rate, hence reduced equipment size and pressure of operation.	Requires secondary source of D; catalyst used.

The remainder of this report deals with commercial production by the GS process.

2.2 History of Heavy Water Manufacture

It was the interest in heavy water as a neutron moderator that instigated large scale research and development aimed at a practical large scale process for its production.

Prior to this its main use had been as a tracer in biochemical processes as well as to scientists involved in isotope research, but the quantities required had not justified its production on a large scale.

This early development took place largely in the United States, where the first large commercial plants were built. Smaller scale development of the electrolysis process also took place in Canada and Norway using hydro-electric power. In recent years Canada has taken the major share in heavy water process development, and both France and India have undertaken development programs and built small commercial plants.

The first processes which produced heavy water on a large enough scale to be considered commercial were electrolysis and vacuum distillation of water.

This was primarily because of their simplicity, which meant that commercial plants could be built with little or no development lead time. However, for concentration of heavy water throughout the full range of concentration between a natural feed (150 ppm) to reactor grade (99.85%) they are far from being economic.

They remain the most attractive process for the final stages of enrichment from say 15% to reactor grade, and thus are used in conjunction with the GS process for final upgrading of heavy water, or for reconcentrating heavy water which has leaked from operating reactors and been recovered.

Of the other processes, hydrogen distillation and the GS process initially appeared to offer economic advantages over electrolysis and distillation.

The eventual selection by the United States Atomic Energy Commission of the GS process was based on the following: (2)

a) The water distillation process, though most completely developed and most dependable, was high in capital cost and very high in thermal energy requirement compared to the alternatives.

b) The hydrogen distillation process was reasonable in operating cost, but certain important items of technology lacked development. The adequacy of hydrogen supply was questionable, and the sources were scattered. The determining conclusion was that the hydrogen distillation units could not be completed in time to meet the scheduled need for heavy water.

c) The GS process, while lacking a desirable degree of confirmation from the pilot plant, appeared to be feasible, with lower capital and operating costs than the water distillation process.

The United Stated pilot plant program on the GS process was therefore accelerated and two production plants, Dana in Indiana and Savannah River in South Carolina were built in 1951 and 1952. (2)

Although these operated successfully, no further plants were built in the USA because their commercial nuclear program eventually centered on the enriched uranium, light water moderated reactor. The Dana plant was shutdown, and two thirds of Savannah River decommissioned, leaving the other third, about 180 tons per year production capacity, to satisfy the remaining world demand for heavy water. Most of this production has been bought by Atomic Energy of Canada Limited (AECL) to meet the needs of its heavy water reactor program, which is the largest nuclear program in the world based on heavy water reactors.

In the 1960's, Canada commenced building its own heavy water production plants when it became apparent that much larger facilities would be required to meet the needs of its expanding nuclear program.

The first plant to be committed for construction was at Glace Bay, N.S. This plant of nominal capacity 400 tons/year was owned by Deuterium of Canada Limited, a company created by the government of Nova Scotia to build and operate the Glace Bay plant.

The design and construction of the plant was carried out by American companies but multiple problems prevented the plant from ever operating and producing heavy water.

The plant was taken over in 1970 by AECL which commissioned Canatom Monmax to redesign and reconstruct the plant. It is now expected that the plant will be in operation before the end of 1975.

A second plant of 400 tons/year capacity was built by Canadian General Electric Company at Port Hawkesbury, N.S. and commenced production in 1970.

AECL also committed for construction an 800 tons/year plant at Bruce, Ontario which commenced operation in 1973. Operation and ownership of the plant has been taken over by Ontario Hydro, who are currently building additional plants on the same site.

The latest plant to be committed, the LaPrade plant, is being constructed by Canatom Monmax for AECL at a site on the St.Lawrence river near Gentilly, Quebec. This plant is also of nominal capacity 800 tons/year and is expected to commence production in 1978.

All the above plants utilize the GS process.

2.3 Source Concentration

One of the important factors in the economics of the GS process is the isotopic concentration of the feed water source. This varies throughout the waters of the world due to natural concentration effects of weather. In Canada the concentration increases gradually eastwards from about 130 ppm (parts per million) at the West coast to 150 ppm at the east coast.

The concentration is generally higher in sea water than in fresh water.

It was for this reason that Nova Scotia was the most attractive location for the first Canadian plants, and for the selection of sea water

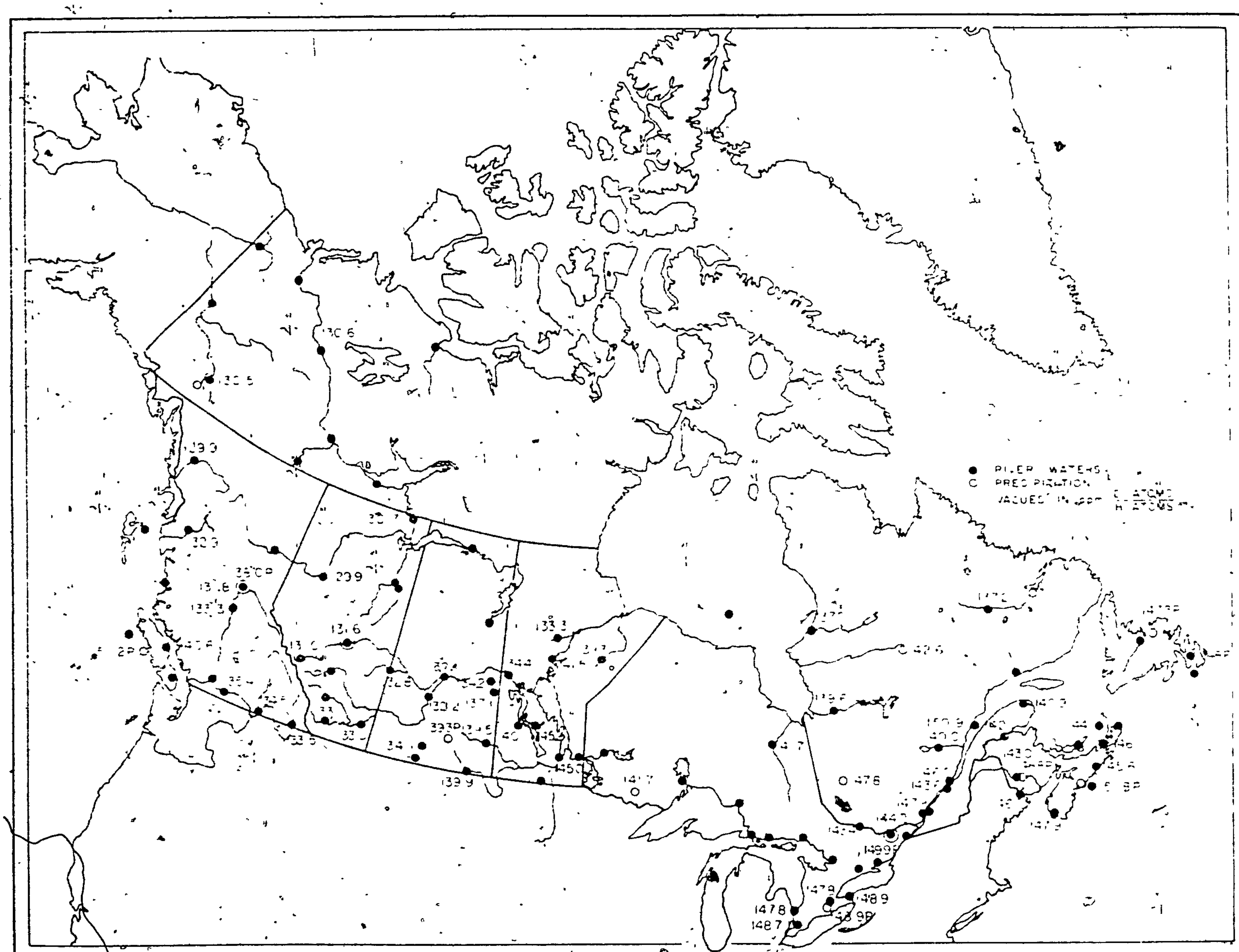


FIG 1 DEUTERIUM CONCENTRATION IN CANADIAN WATERS[4]

as the feed for the initial Glace Bay plant.

Figure 1 shows the results of a survey (4) carried out to determine the deuterium content of Canadian waters.

CHAPTER 3 THE GS (GIRDLER-SULPHIDE) PROCESS

3.1 Process Fundamentals

Figure 2 shows a simple schematic (2)(4) of one stage of a GS production unit. A typical plant would contain from two to five stages (2) with three being the most likely number.

Each stage consists of a hot and a cold tower in which the two components, water and hydrogen sulphide, are contacted countercurrently.

Each tower contains approximately one hundred contacting units, which in modern plants are simple sieve trays. The efficiency of each tray is in the order of 60%, (i.e. the exchange reaction on each tray only reaches 60% of equilibrium before the components leave the tray.)

The fresh water feed stream, which is typically at a concentration of 150 ppm, enters the process at the top of the cold tower. It receives prior treatment to remove impurities, and dissolved gases, and to adjust pH. At the cold tower temperature of 30°C, the deuterium migrates from the hydrogen sulphide to the water. At the bottom of the cold tower, the deuterium in the water stream has been enriched by a factor four to a concentration of approximately 600 ppm. At this point, a product stream amounting to about one sixteenth of the feed stream is withdrawn and fed to a second stage for further enrichement.

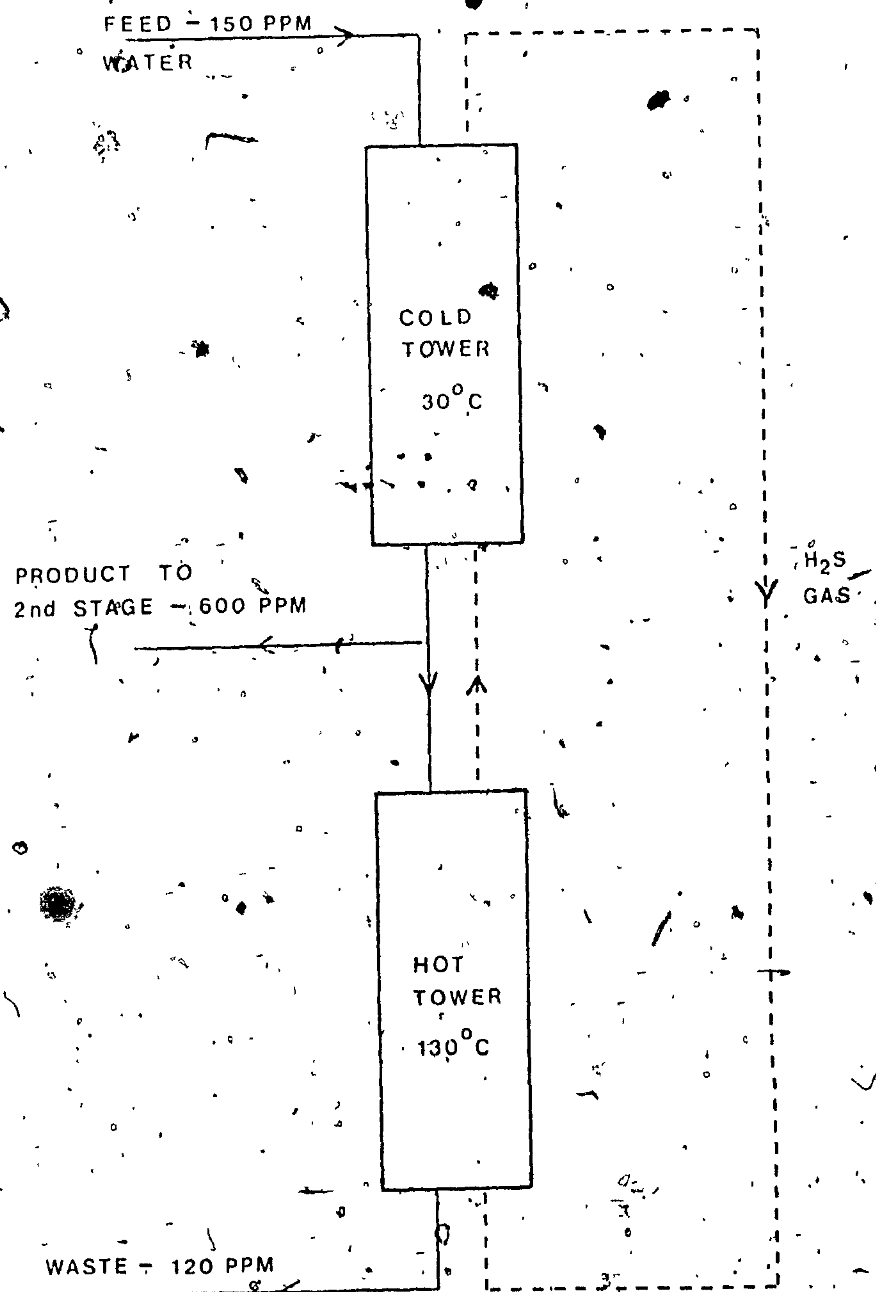


FIG 2 SCHEMATIC FLOWSHEET FOR DEUTERIUM SEPARATION

The remainder of the enriched stream is heated to the hot tower temperature of 130° C and again contacted countercurrently with hydrogen sulphide. At this temperature the deuterium migrates to the hydrogen sulphide. At the bottom of the hot tower, the water stream has been depleted to about 120 ppm, which is 20% below the feed concentration, and is discharged as waste.

3.2 Factors which Affect Production

3.2.1 Temperature and Pressure

As explained in section 1.4, the maximum recovery of heavy water from the feed is fixed by the difference between the values of the separation factor at the two temperatures of operation, 30°C and 130°C. By increasing the spread of the operating temperatures, a greater recovery is theoretically possible.

However, the H_2S-H_2O phase diagram [4], figure 3, plays a crucial part in limiting the practical spread of the process operating temperatures.

The capital cost of the plant is largely dependent on the volume of the equipment which must be provided, and this volume can be minimised by operating the process at high pressure. At high pressure and low temperature, a hydrogen sulphide/water mixture forms a solid hydrate which prevents operation of the proces. The maximum economic pressure is about 300 psia, corresponding to a hydrate formation temperature of 30°C. Further increases in pressure require large increases in the cold tower temperature which reduces recovery of deuterium.

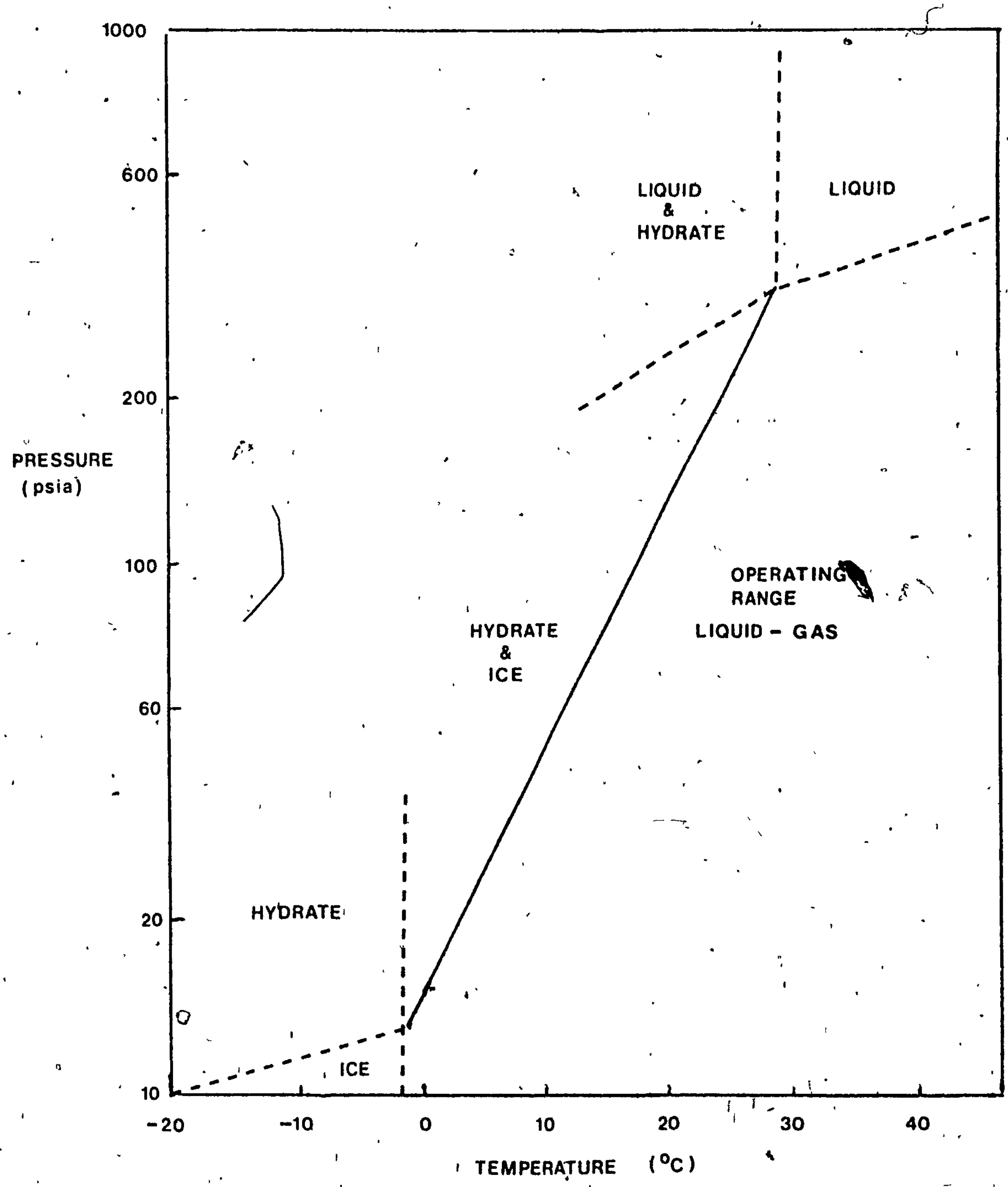


FIG 3 $H_2S - H_2O$ PHASE DIAGRAM

To reduce the cold tower temperature below 30°C requires large reduction in pressure to prevent hydrate formation, and results in uneconomic size increase in all the process equipment.

With the pressure of the overall system fixed by the optimum combination of pressure and temperature in the cold tower, the optimum hot tower temperature is determined by balancing the beneficial effect of increasing the difference between the values of the separation factor, and the detrimental effect of increasing the humidity of the gas stream which necessitates larger equipment to handle the larger volume flows. The optimum hot tower temperature lies between 130°C and 140°C, and is normally chosen close to 130°C.

Any malfunction in the process which prevents either the optimum pressure or the optimum temperatures being achieved can seriously affect production of heavy water. Impurities in the process which can lead to foaming of the process liquid stream in the towers can seriously limit the pressure of operation.

3.2.2 Gas & Liquid Flow Ratios

To obtain maximum extraction of deuterium the total quantity of deuterium in the liquid stream must equal as closely as possible that in the gas stream. [2]

Since there is a transfer of deuterium from one stream to the other at each contact tray, this optimum operating condition cannot exist throughout the complete contact on each tray. The operating flow rates are therefore chosen so that the deviations from this optimum condition in the fluids entering and leaving the tray are minimized.

Because the concentrations of deuterium in each stream are related by the separation factor, the optimum gas and liquid flow rates are related by the separation factor.

If the process were operating throughout with the deuterium conecntrations in equilibrium, the relationship between the liquid and gas flow rates and the separation factor for maximum extraction would be:

$$\frac{1}{\alpha} = \frac{L}{G} \qquad (6)$$

However, the concentrations never reach equilibrium in either tower and the values of the liquid and gas flow rates must be chosen to equalize the deuterium quantities in each stream in actual operation. The relationship therefore becomes:

$$\frac{1}{\alpha_h} > \frac{(L)}{(G)_h} > \frac{(L)}{(G)_c} > \frac{1}{\alpha_c} \qquad (7)$$

The ratio of the term $\frac{(1)}{(\alpha)}$ to the term $\frac{(L)}{(G)}$ in each tower determines the number of trays required in the tower. The capital cost of the plant is minimized when the hot and cold towers contain equal numbers of trays, [(2)] hence the ratios of $\frac{1}{\alpha}$ to $\frac{L}{G}$ in both hot and cold towers must be equal.

In an operating plant where the number of trays has been determined on the basis of a particular liquid to gas flow ratio, deviations from this optimum flow ratio result in serious drops in recovery of deuterium.

This effect is presented numerically for a cold tower of the Dana plant in the USA, [(2)] in table 3, and graphically in figure 4.

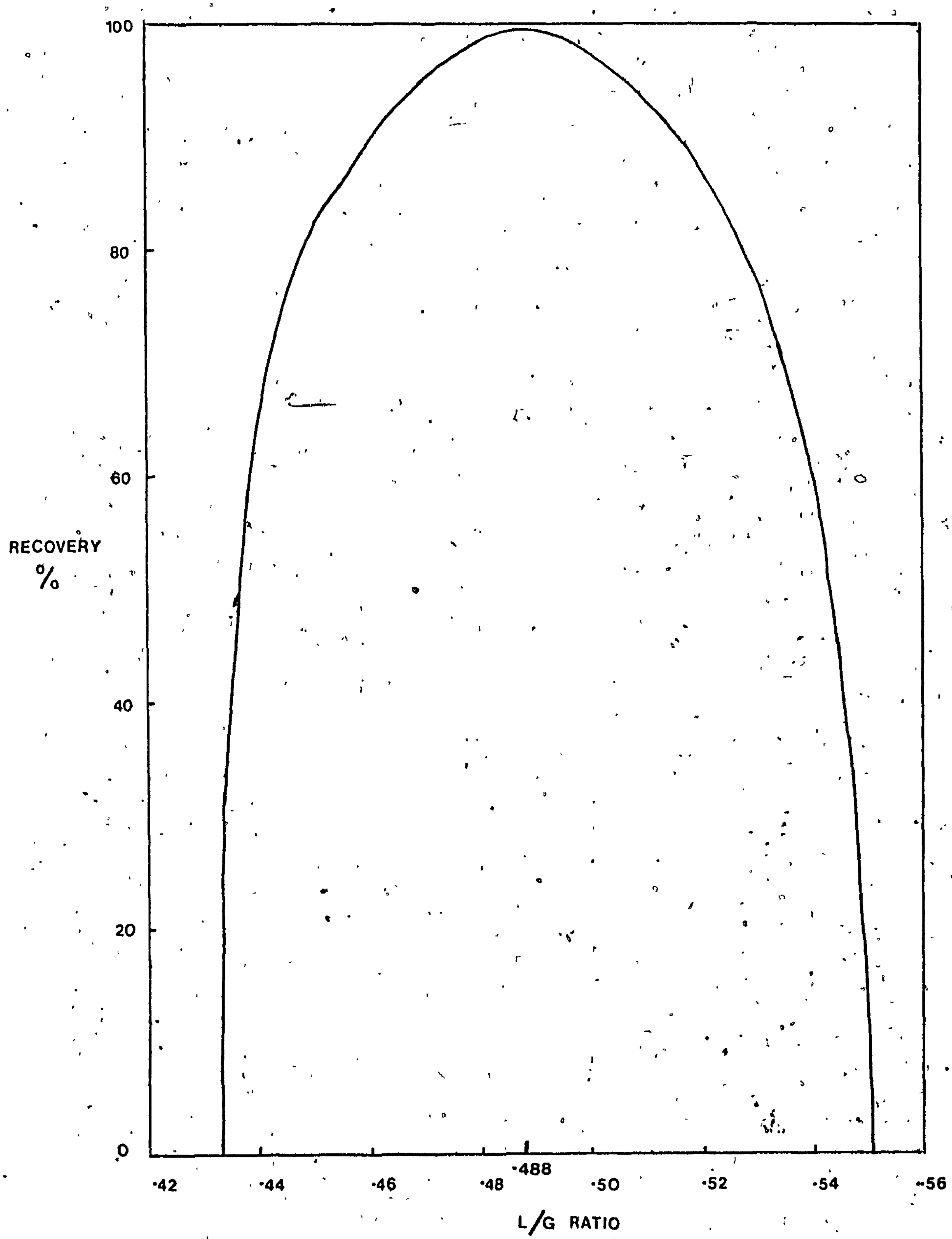


FIG 4 EFFECT ON DEUTERIUM RECOVERY OF DEVIATIONS IN THE LIQUID/GAS FLOW RATIO

TABLE 3

Effect of Variation of Liquid to Gas Flow Ratio on Recovery of Product

$(L/G)_c$ (value)	(% of design optimum)	Recovery of deuterium (% of design optimum)
0.436	89.3	0
0.460	94.5	90.2
0.481	98.6	97.5
0.488*	100	100
0.543	111.5	65
0.553	113	0

* design optimum

CHAPTER 4 - FLOW MEASUREMENT IN HEAVY WATER PLANTS

4.1 Introduction

In Chapter 3, the importance of the liquid to gas flow ratio to the attaining of the design recovery of product from the plant was explained. The effect of deviations from the design value of liquid to gas flow ratio is clearly shown in figure 4. It is obvious from this figure that the yield of the plant is very dependent on accurately maintaining these flow ratios.

The accuracy of flow control is limited by the accuracy of available flow measurement techniques which can be applied to this process. In this chapter, the methods of flow measurement which are used in existing plants will be evaluated and their inadequacy demonstrated.

Of the very large number of flow measurement techniques which exist, a small selection which offer a potential solution to the problem will also be investigated to select the flow measurement techniques which are most suitable for further development for heavy water plant applications.

4.2 Techniques Used at Existing Plants

To date reliance has been placed on the venturi tube and the square edged orifice plate as the primary flow elements in gas and liquid streams respectively. Because most orifice plates are used in horizontal lines, and because the liquid streams can contain suspended solid particles, most of the orifice plates are of the segmental type. However, the accuracy and repeatability of these devices has not been quite adequate to ensure that the plant was operating at its optimum liquid to gas flow ratio.

Developing the tolerances for these elements from their equations of flow will amplify this problem.

4.3 Tolerances

The basic flow equations for flow elements can be developed from considerations of energy and momentum.

Assumptions made in deriving the equations (6) of flow are:

1) The pipe section is horizontal so that gravity effects need not be considered.

2) There is no external work done on or by the fluid.

3) The flow is steady, axial, and the velocity profile remains flat and normal to the pipewall.

4) There is no heat transfer to or from the fluid.

5) For liquids only there is no temperature change of the fluid along the axis of the element.

The general equation for mass flow for liquids is therefore:

$$m = aC\sqrt{2g\,\rho\,(P_1 - P_2)}\sqrt{\frac{1}{1-(a/A)^2}} \qquad (8)$$

Where m = mass rate of flow

C = discharge coefficient

g = gravitation acceleration

ρ = fluid density

$P_1 - P_2$ = pressure drop

a = throat area

A = pipe area

In most meters the throat and pipe are circular, and the term $(a/A)^2$ is usually replaced by $(d/D)^4$, $= \beta^4$ where β = the diameter ratio.

The term $\sqrt{1/(1-\beta^4)}$ is called the velocity of approach factor.

For the considerations of this report, segmental orifices will be studied rather than circular ones, hence the velocity of approach factor must be related to the area ratio.

For adiabatic flow of an ideal gas the above equation for liquid flows must be modified by an expansion factor Y[6] to become:

$$m = aC\sqrt{2g\rho\,(P_1-P_2)}\,.\,\frac{1}{\sqrt{1-(a/A)^2}}\,(Y) \qquad (9)$$

$$\text{where } Y = \left[\left(\frac{P_2}{P_1}\right)^{2/\gamma}\frac{(\gamma)}{(\gamma-1)}\;\frac{\left(1-\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right)}{\left(1-\left(\frac{P_2}{P_1}\right)\right)}\;\frac{\left(1-(a/A)^2\right)}{\left(1-(a/A)^2\left(\frac{P_2}{P_1}\right)^{2/\gamma}\right)}\right]^{\frac{1}{2}} \qquad (10)$$

$\gamma = \frac{Cp}{Cv}$ = ratio of specific heats of an ideal gas.

For a real gas ρ would be replaced by $\frac{P}{ZRT}$ where Z is the compressibility factor[6] for the gas at the pressure and temperature conditions of P and T respectively, and R is the molecular weight gas constant.

The overall tolerance on the flowrate as measured by either of these meters can now be computed by analysis of the tolerances of each of the individual terms making up the equations.

The tolerances taken here for discharge coefficients and expansion factors are taken from "Fluid Meters - Their Theory and Application", (6) published by the American Society of Mechanical Engineers, computed according to the recommended methods of the Fluid Flow Measurement Committee of the International Organization for Standardization. (ISO/TC-30).

4.3.1 Segmental Orifice Plate

The tolerances of the individual terms are shown below:

Term	Tolerance (%)	Effect Factor	Square
Dimensional tolerance (linear) of orifice	± 0.1	2	0.04
Differential pressure (p_1-p_2)	± 0.25	1/2	0.0156
Density	± 0.2	1/2	0.01
Discharge Coefficient	± 2	1	4
Overall Tolerance	± 2.02		4.0656

The value of ± 2.02 % is for a new uncalibrated orifice. Calibration eliminates the effect of the dimensional term and partly eliminates the more serious effect of the discharge coefficient. However, the in-service effects of corrosion, sludge deposition and possible formation of gas bubbles in the liquid stream, more than offset the benefit of calibration, and the value computed can therefore be taken as a minimum.

4.3.2 Venturi

Data presented here for a venturi is modified from that given in the ASME reference text because of the size extrapolation and different construction. The venturis used for gas flow measurement in heavy water plants are nominally of 48 in. diameter (pipe), and constructed from plate and pipe. The inlet and outlet cones are welded plate construction with the throat section being a straight piece of pipe. Because of this mitre construction, the exact effective throat diameter is difficult to assess.

In addition the material of construction is carbon steel and is susceptible to corrosion, making dimensional tolerances even less certain.

Calibration can offset the unknowns due to the mitre construction, but the corrosion effect can still place a tolerance of 1% on the throat dimension.

The tolerances for the venturi are compiled below.

Term	Tolerance (%)	Effect Factor	Square
Dimensional tolerance (linear) of throat	$\pm$ 1.0	-2	4
Differential pressure (p_1-p_2)	$\pm$ 0.25	1/2	0.0156
Density	$\pm$ 0.5	1/2	0.0625
Coefficient of discharge	$\pm$ 1.5	1	2.25
Expansion Factor	$\pm$ 0.4	1	0.16
Overall Tolerance	2.55%		5.4881

4.4 Effect of Tolerances on Production

Taking the tolerance values computed above and applying them to the L/G ratio gives a tolerance on the L/G ratio of $\pm$ 4.69%.

Referring now to figure 4, which indicates the optimum L/G ratio to be 0.488, we see that for the spread of tolerance of the L/G ratio, the plant production could be reduced to as low as 90% of design.

4.5 Practical Solution used in Plants Now Operating

To overcome this difficulty, an indirect method of flow measurement was adopted [(2)] to give fine control of production.

At the optimum value of L/G the concentrations of deuterium at the middle of the hot tower and the middle of the cold tower are equal.

After approximate adjustment of the flow ratio using the flow measurement equipment, the process is finely balanced by sampling at the mid columns and adjusting flows until the concentrations are equal.

Although this method ensures that the plant is operating at its most efficient, it nevertheless possesses several disadvantages:

a) The approach to the optimum operating condition is necessarily slow because of the significant time lag between taking a sample and obtaining the results by analysis, adjusting the flows, re-sampling, and so on.

b) This sampling, which is carried out every shift to ensure that no deviations from the optimum conditions have occurred, places additional workload on the plant operators, adding to the operating staff requirements and therefore to the production cost of heavy water.

c) The provision of a sample system adds to the capital cost of the plant.

d) The sampling operation and the sampling system itself present undesirable hazards, since they involve penetration of the process pressure envelope. Mechanical damage to the sampling system or maloperation of the system could result in escape of the toxic H_2S to the environment.

Consideration is being given to the provision of continuous sampling systems to overcome the time lag discussed in (a) and the operator workload discussed in (b). However, this would necessarily be a more complex and expensive system. Because of the long runs of small bore sampling tube between the process areas and the remote control building it would also be more susceptible to damage and present an added safety and unreliability problem.

4.6 Further Development in Flow Measurement

The obvious alternate solution to this problem is the development of adequate flow measurement systems for heavy water plant process systems.

The main criteria for a flow measurement system are:

(a) Its overall tolerance should be less than ±1% (after calibration).

(b) It should be available in sizes suitable for monitoring gas flows up to 35 000 ACFM in line sizes up to approximately 48 in. diameter, and suitable for measuring liquid flows up to 2 500 USGPM in line sizes up to approximately 24 in. diameter.

(c) Pressure drop should be low because of the high flows and pumping costs. Its cost should at least be competitive with the cost of line size venturi and orifice meters which it will replace.

(d) It should stand up to the process conditions, in particular the corrosivity of the process fluid.

With these objectives in mind, the Canadian heavy water industry has experimented in recent years with a number of flow measurement techniques. The one parameter which has been common to all of these techniques is that they have not been dependent on pressure or pressure difference measurements. This obviously aids in standardization, because the primary element does not necessarily have to be line size. It also eliminates inaccuracies due to the differential pressure measurement.

4.6.1 The Target Flow Meter

Figure 5 shows a schematic arrangement of a target flow meter, and figure 6 shows one of these devices manufactured by the Ramapo Instrument Corporation.

The force produced by the impact of the moving fluid on the target causes the target to deflect against a restraint. The deflection is a measure of the force and hence of the fluid velocity.

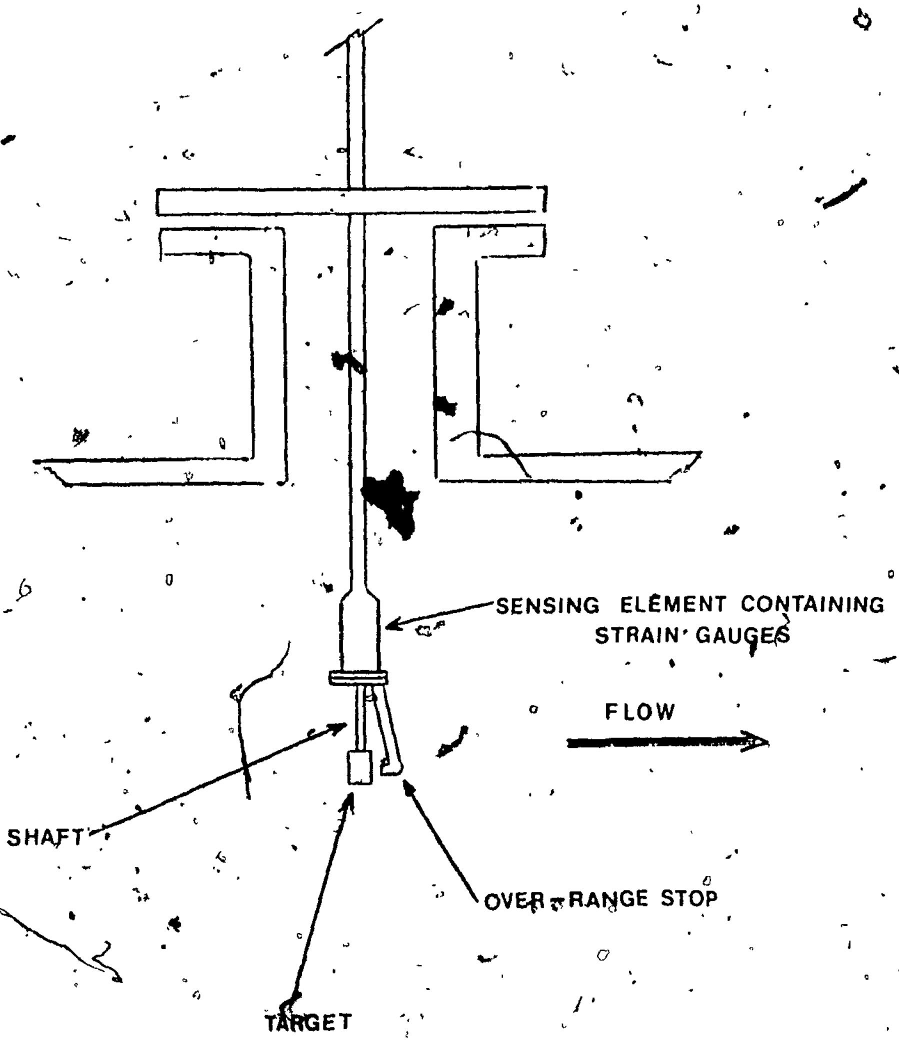


FIG. 5 TARGET FLOWMETER – SCHEMATIC

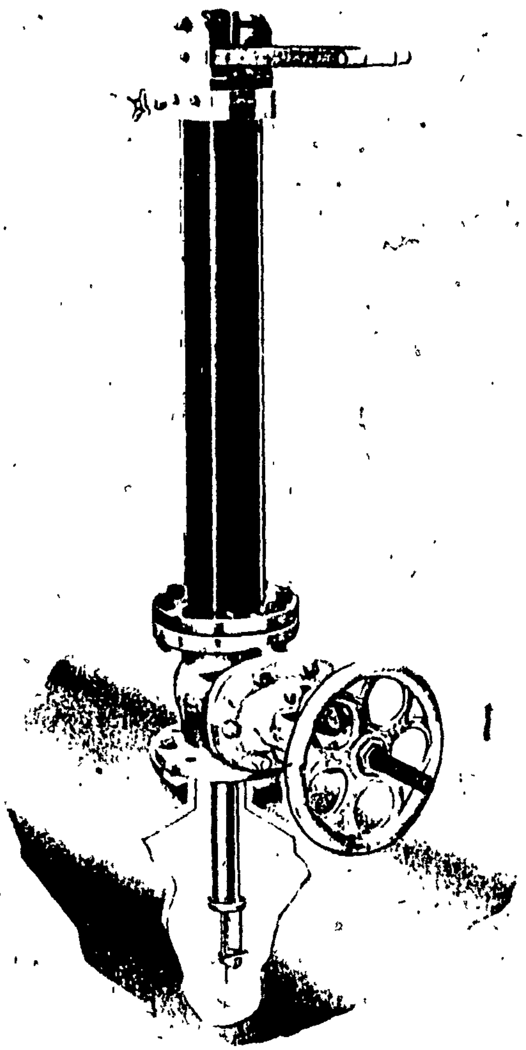


FIG 6 TARGET FLOWMETER – RAMAPO INSTRUMENT CORPORATION

Because such an element senses velocity rather than flow, it is susceptible to velocity profile, and can therefore only be used successfully where the profile is flat. In heavy water plants they have been tried in gas flow measurement where the target is very small in comparison to the line size and is inserted so that it is remote from the pipe wall, and unaffected by any velocity profile changes near the wall.

The general mass flow equation [6] for this element is:

$$m = C\frac{(D^2-d^2)}{d}\sqrt{\frac{\pi}{4}\,\frac{2g\ F}{\rho}} \qquad (11)$$

where F is the force on the target, and for volume flow:

$$q = C\frac{(D^2-d^2)}{d}\sqrt{\frac{\pi}{4}\quad 2g\ F/\rho} \qquad (12)$$

Although needing no pressure taps, this meter must still produce and transmit a signal.

As used in heavy water plants, the signal was transmitted by strain gauges, connected in a bridge circuit, bonded to the target shaft.

However, operating experience demonstrated these devices to be erratic and unreliable, sensitive to temperature and pressure variations, and with construction and material deficiencies which permitted ingress of process fluid to the strain gauge chamber, resulting in erronious measurement.

Manufacturer's claimed accuracy is $\pm$ 1/2%, so this device remains open for further consideration once the problems of construction are resolved. Meters of this type are in use in two Canadian Heavy Water plants, but other methods are used to cross check their readings (pressure drop across blower) until the flow measurement problem is overcome.

4.6.2 The Vortex Shedding Flow Meter

Like the target meter, this is an insertion type meter, and thus lends itself to standardization for all line sizes. It offers potential as a gas flow meter.

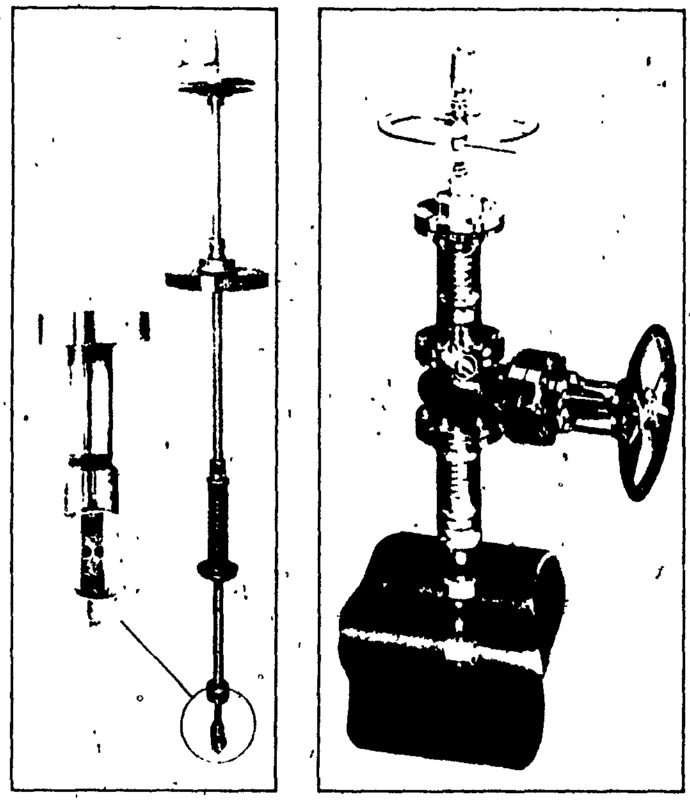
Manufacturer's claimed accuracy is ± 1/2%.

A schematic diagram of a vortex shedding flowmeter, and illustrations of such a meter manufactured by Eastech Incorporated [8] are shown in figure 7.

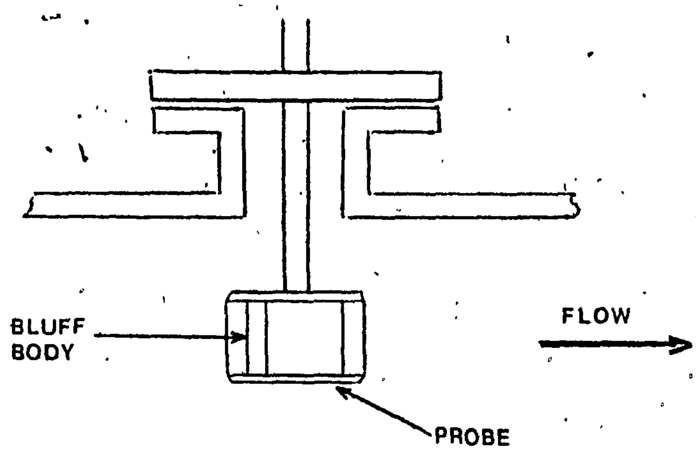
This meter makes use of the Karman Vortex street [8][9] produced by a bluff body in a flow steam. The leading edges of the body alternately shed vortices which cause localized flow oscillations in the fluid passing the leading face of the bluff body. Electronic, self-heated, thermistors, embedded in the leading face of the bluff body, detect the flow oscillations as a temperature difference between their own self-heated value and the temperature of the flowing fluid. The thermistors generate a pulse train the frequency of which is proportional to the flow.

This device can be used at Reynolds numbers above 5000, above which the dimensionless Strouhal number remains constant at a value of 0.21. Figure 8(a) shows a typical Karman Vortex street downstream of a bluff body, and figure 8(b) shows the variation of the Strouhal number with Reynolds number. The Strouhal number [9] relates velocity to the dimension of the bluff body and its frequency of vibration, by the equation:

$$S = \frac{nd}{V} \tag{13}$$

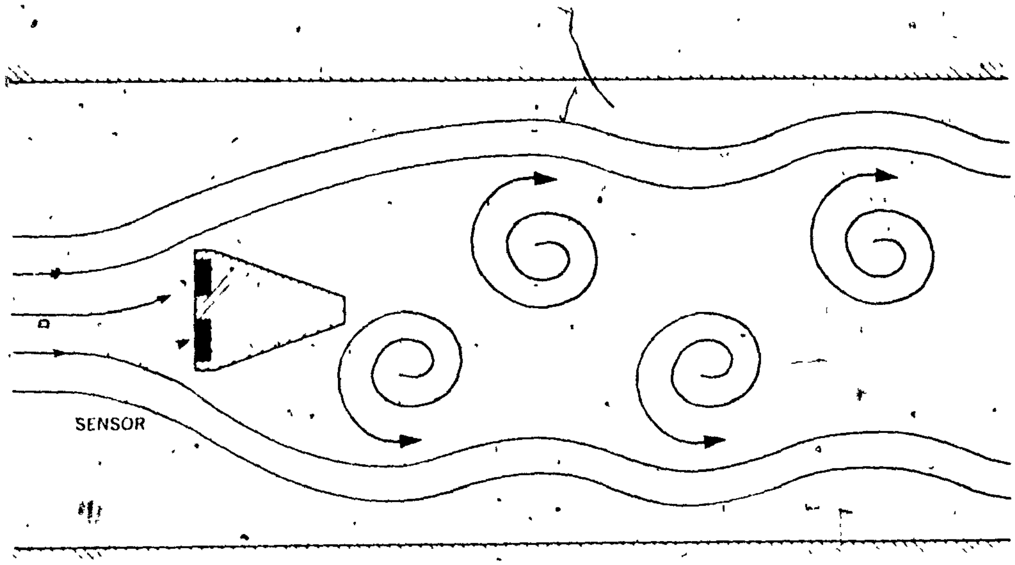


(a) RETRACTABLE MODEL BY EASTECH INCORPORATED

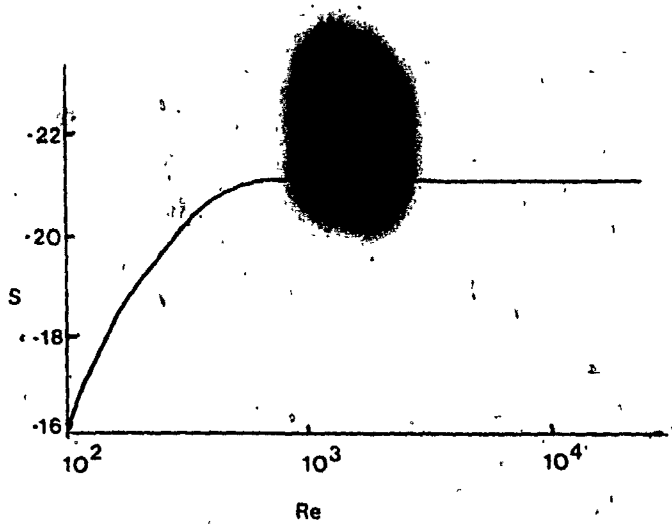


(b) SCHEMATIC DIAGRAM

FIG 7 VORTEX SHEDDING FLOWMETER



(a) KARMAN VORTEX STREET



(b) RELATIONSHIP BETWEEN REYNOLD'S No. & STROUHAL No.

FIG 8 VORTEX SHEDDING FLOWMETER

Where S is the Strouhal number

n is the frequency of vibration

d is the diameter of the bluff body

(assumed cylindrical)

V is the velocity of the fluid

Translation into terms of volumetric flow rate q and line diameter D we have:

$$q = \frac{\pi}{4}\frac{n\ d\ D^2}{S} \quad (14)$$

Use of a vortex shedding meter is presently prohibited only by doubts concerning its material of construction, in particular the bonding between the thermistors and the bluff body.

4.6.3 The Pitot Tube

The pitot tube [6] measures the velocity head of a flowing fluid by detecting the difference between the dynamic and static pressure at a point in the fluid.

This is again an insertion type of meter, but it does require additional pressure sensing and transmitting devices, hence its limits of accuracy are not as potentially good as those of the target and Vortex shedding meters.

The type of pitot tube with multiple openings in the dynamic pressure sensor to average any variations due to velocity profile is being tested for use on heavy water plants, and is illustrated schematically in Figure 9. This device also deviates from standard practice in measuring downstream pressure rather than static pressure, to achieve a somewhat high pressure differential.

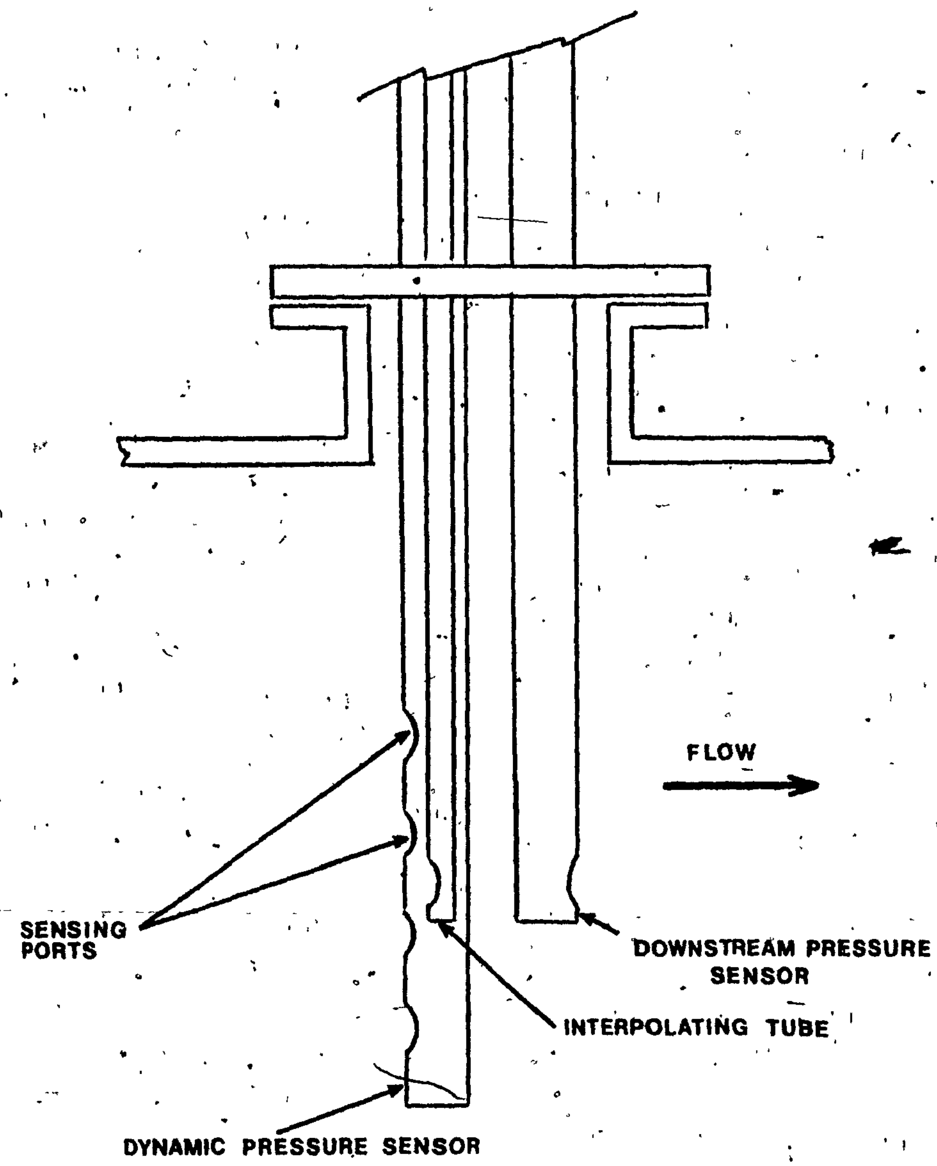


FIG 9 PITOT TUBE – SCHEMATIC DIAGRAM

However, it's overall accuracy is still marginal (not less than 1%).

Plugging of the sensing holes in the pitot tube was considered the most potentially serious problem with this device, but the fears appear to be unfounded, since particulate matter appears to follow the streamlines which divert around the stagnation points in front of the holes. The device has not been studied further because of its marginal accuracy.

4.6.4 The Magnetic Flow Meter

The magnetic flow meter is an in-line device used to measure the flow rate of conductive liquids by creating a magnetic field across the meter tube and detecting the voltage difference that develops as a result of the flow of the conductive liquid through the field. The arrangement of this device is shown in figure 10.

In practice the coils which generate the magnetic field are outside the meter tube and the electrodes which measure the induced e.m.f. are set into an insulating sleeve. Hence there is no obstruction at all to the flow, and by measuring the induced e.m.f. across the full diameter, there is no velocity profile error.

The flow is given by the equation: (6)

$$q = \frac{\pi}{4} \frac{D^2}{\delta} \frac{e}{B} \quad (ft^3/sec) \qquad (15)$$

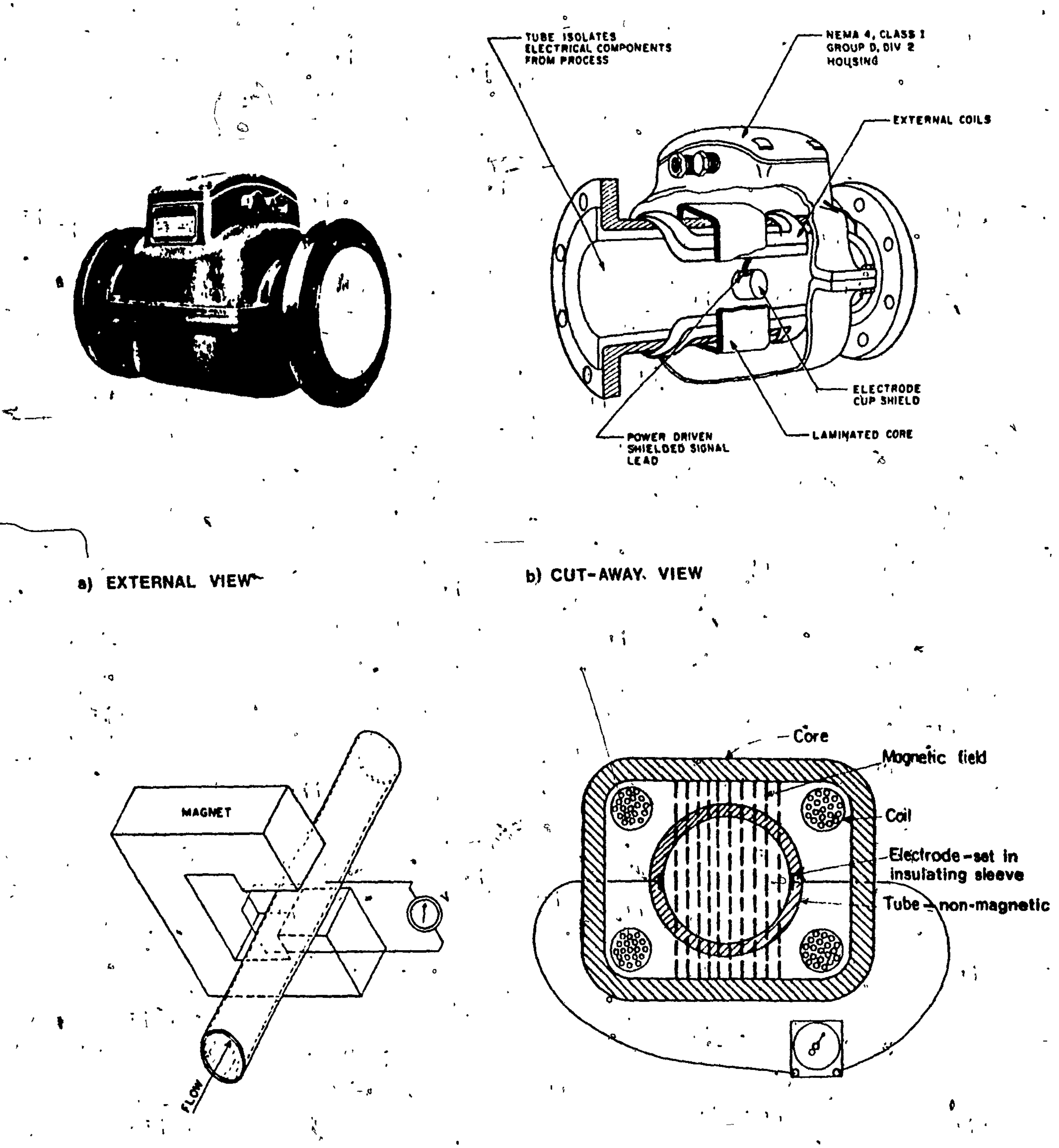
where δ is the distance between the electrodes (ft)

e is the induced e.m.f. (volt)

B is the flux density (weber/ft^2)

In practice δ is almost always equal to D so the equation reduces to

$$q = \frac{\pi D e}{4 B} \qquad (16)$$



a) EXTERNAL VIEW

b) CUT-AWAY VIEW

c) SCHEMATIC VIEW

d) SECTIONAL VIEW

FIG 10 MAGNETIC FLOWMETER

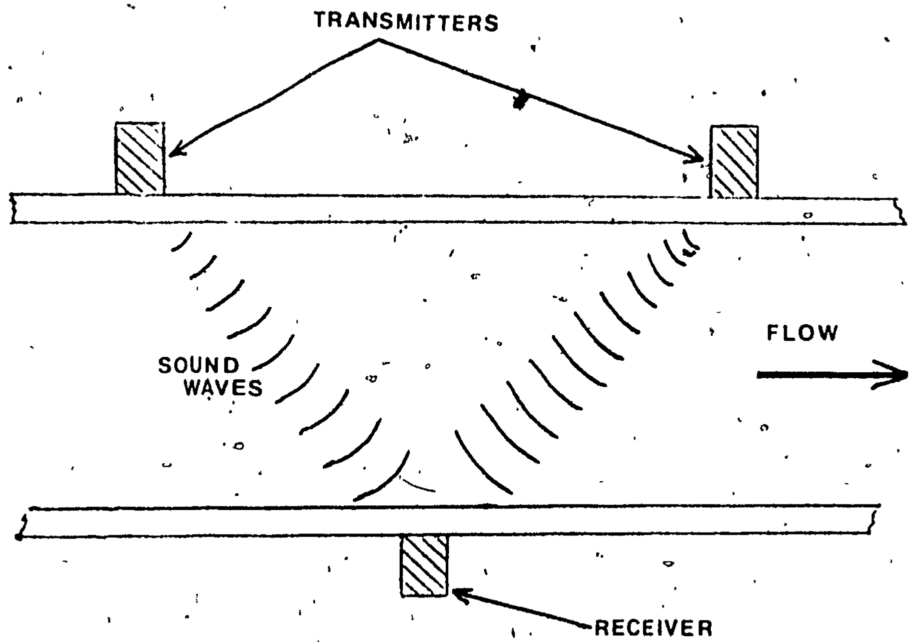
The accuracy of this meter is ±1%, adequate for heavy water plant use, but its very high cost precludes its adoption for all liquid flow measurement. However, it has been installed in locations or service where an orifice would not suffice, i.e., where the range of flows to be measured was too great, or where insufficient length for a meter run upstream or downstream was available.

4.6.5 Ultrasonic Flowmeters

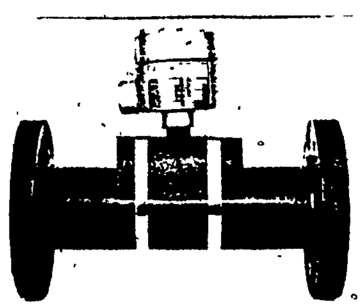
Two ultrasonic flowmeters based on completely different theories of operation have been investigated. Advantages common to both are that they are portable clamp-on devices which cannot obstruct the process fluid flow and cannot be corrosively attacked by it, meter lengths upstream or downstream are not required, no calibration is necessary, output is a linear function of flow, and they are both sufficiently accurate (±1%) for heavy water plant needs.

A common disadvantage is their high cost, since in an operating heavy water plant, advantage cannot be taken of their portability, and they must be permanently installed at all locations where a liquid flow reading is needed.

The first meter,(10)(11) figure 11, works on the Doppler principle. The functional elements of the meter are three transducers, two for transmitting the ultrasonic signal, and one for receiving it. The transmitters are located on the opposite side of the pipe to the receiver, one upstream of it and one downstream. They transmit their signal in an alternating fashion at a constant frequency.



(a) SCHEMATIC DIAGRAM



(b) CLAMP-ON MODEL BY DATASONICS CORPORATION

FIG 11 ULTRASONIC FLOWMETER UTILIZING THE DOPPLER EFFECT

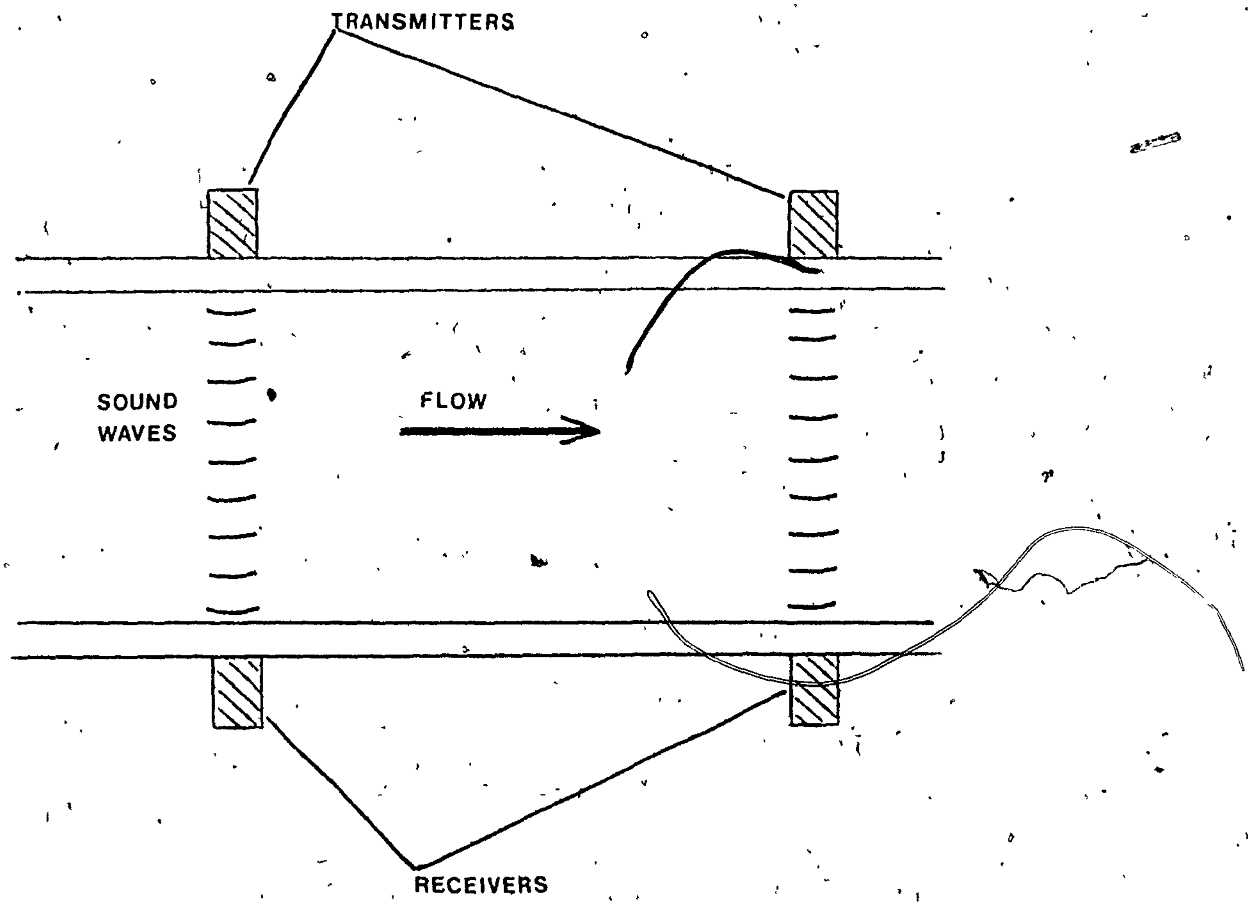


FIG 12 ULTRASONIC FLOWMETER – CROSS CORRELATION TYPE – SCHEMATIC

When the fluid is flowing the frequency from the upstream transmitter is reduced at the receiver due to the Doppler effect, and that from the downstream receiver is increased. The difference in frequencies is directly proportional to flow.

In the second meter, figure 12, four transducers are used in pairs, spaced a short distance apart along the axis of the pipe. An ultrasonic signal is maintained between each pair of transducers. In static fluid or in a completely homogenous stream of moving fluid, the signals picked up by the receivers will remain perfectly steady and constant in frequency.

However, a moving liquid stream is heterogenous, containing eddies, and pockets of liquid at slightly different temperature to the bulk stream. These inhomogeneities affect both the amplitude and the phase of the received signal.

Circuitry is available which can detect phase shifts of less than 1°; a shift of this magnitude would be produced if the ultrasonic beam passed through an inhomogeneity of 1.5mm thickness at a temperature 1°C removed from the bulk fluid temperature.

Eddies, because of the Doppler effect, produce other identifiable phase change patterns.

Thus the ultrasonic signal is being used to detect the naturally existing tracers present in the fluid stream as inhomogeneities. Since the inhomogeneities travel significant distances along the line without any major change, the signals from the receiving transducers show almost identical phase patterns, and the time interval between corresponding points on the patterns is inversely proportional to the velocity of the liquid stream.

This device appears to offer great potential, especially when located where flow disturbances can be expected, such as immediately downstream of a valve or an elbow. In this sense it is the complete opposite of most head type elements which require a long meter length to produce a steady flow.

Both types of ultrasonic meter described above will function only if the liquid is continuous between the walls of the pipe. Hence its only limitations occur when there are gas bubbles or suspended solids in the flow.

4.6.6 Miscellaneous Flow Measurement Techniques which may Warrant Further Development

All the flow measuring devices discussed above have been actively considered for use in heavy water plants. A few others also appear to be worthy of further investigation. This report therefore concludes with a brief summary of these techniques.

4.6.6.1 Cross Correlation Flow Measurement (12)(13)(14)(15)

This is a general name for a flow measurement technique which records a particular characteristic of the fluid stream at two points along the stream and relates the time interval between them to the velocity of flow. The second of the two ultrasonic flowmeters described in 4.6.5 falls into this general catagory.

Any detectable fluctuation in the flow stream can be used as the tracer for such a meter. Advantage can be taken of naturally occurring fluctuations, or they can be artificially induced to ensure a strong signal.

Parameters which can be used are turbulence, density, ultrasonic attenuation, dielectric constant, temperature or solid particles. If provision is made to artificially inject a tracer in pulse fashion, then the possibilities become very extensive.

4.6.6.2 The Vortex Flow Meter

Two completely different meters which can both be accurately described as vortex flow meters have been developed. The first of these, named the swirl meter by its originators, (16), is illustrated in figure 13. This device involves in-line components, the swirl blades and the deswirler, but the sensing device is an insertion type device. The bore of the meter in between the swirl blades and the deswirler must be specially contoured, hence the device would be very expensive in the large sizes needed for heavy water plants. It would also impose a high pressure drop because of the obstruction of the blades and deswirler. However, high accuracy is claimed; further investigation is warranted.

In operation, the swirl blades induce a vortex in the flowing gas. The pitch of the vortex as it moves through the meter depends only on the geometry of the swirl blades, and maintains its constancy over a flow range from Reynolds number 10,000 to Mach 0.12. Heavy water plant gas flows lie within this range, as do most gas flows which are selected for overall economy of operation.

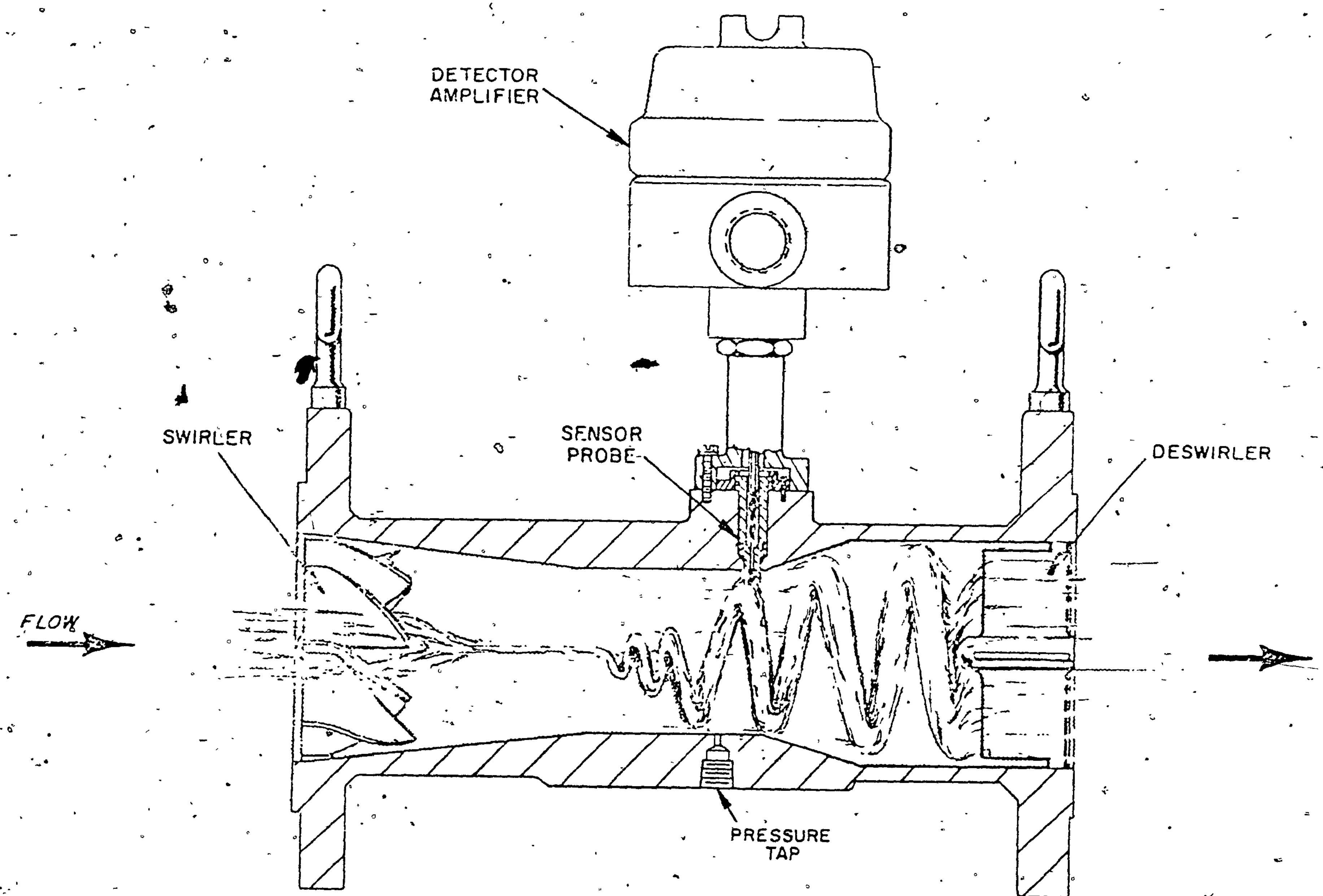
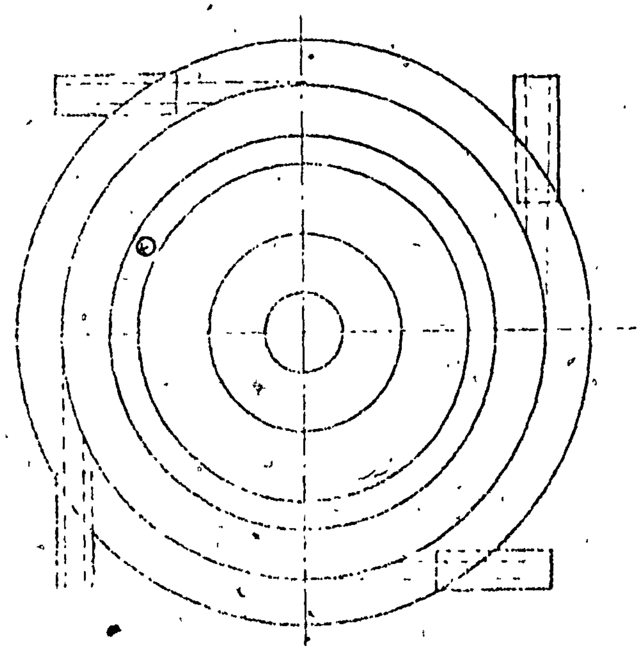


FIG 13 SWIRL METER



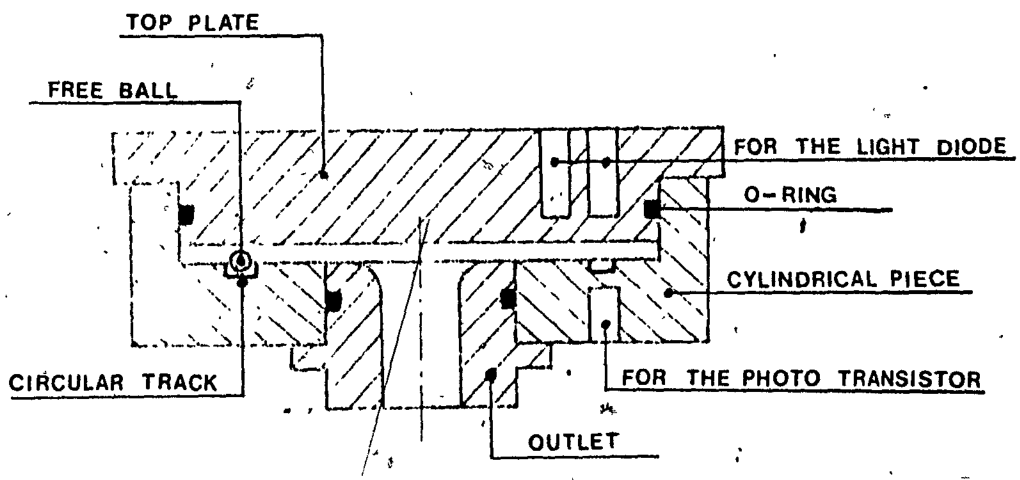


FIG 14 VORTEX FLOWMETER; EXPERIMENTAL MODEL

The vortex moves with the gas at the speed of the gas stream. The sensor simply counts the pitches of the vortex and the frequency is linearly proportional to the gas flowrate.

The second type of vortex flowmeter, which has been developed to an experimental stage by C. Kwok, and D. Nastou at Sir George Williams University (17) (now Concordia University) is illustrated is figure 14.

The flowing fluid enters a circular chamber tangentially through multiple entry ports(4 in the experimental model) creating a swirling flow within the chamber. The fluid exits through a single port at the centre of the chamber. A small ball located on a circular track within the chamber rotates with the swirling flow. The speed of rotation was shown to be essentially linearly proportional to the flow through the device, hence flow could be measured by counting rotations. In the experimental model the rotations could be counted photoelectrically since the chamber was constructed of transparent material.

Drawbacks to the application of this device in heavy water plants are:

a) Its probable cost if sized to accomodate high flows, and high pressures.

b) its requirement for multiple entries (probably easily overcome by using an axial entry with flow deflectors).

c) The difficulty of counting revolutions of the ball in a steel chamber.

d) Its high pressure drop.

It appears to lend itself more readily to the measurement of low flow where pressure drop is not an important consideration.

4.6.6.3 Fluidic Flow Measurement

Two fluidic approaches to flow measurement are presented here.[18][19] Both have the usual advantages of a fluidic device; they have no moving parts, the cost of the devices are low, they can be made from a wide variety of materials.

Because they are an insertion type device, they cause very little pressure drop, and are suitable for monitoring large volume or small volume flows.

Both have a linear output over a wide velocity range, however, one of the devices, which is the simpler and more conventional, requires a fairly high pressure (up to 50 psi) power jet, and even so, it saturates at a flow velocity of about 60 ft/sec. This approximates to the maximum velocity of gas streams in heavy water plants, hence this limitation would be undesirable.

The second device, based on less conventional fluidics, has a wide operating range, from 0.25 ft/sec. to 160 ft/sec. Its output is linear over the whole of this range, and the power jet can be of lower pressure (3 psi) and lower flow.

These devices have been suggested for meteorological use on wind measurements, because of their suitability for measuring very low flows, and one of them has been developed into a commercial anemometer. The simpler of the two devices, (18)(19) called a cross flow sensor, operates on the principle of a fluid amplifier. It seems to be the less suitable of the two for heavy water plant applications.

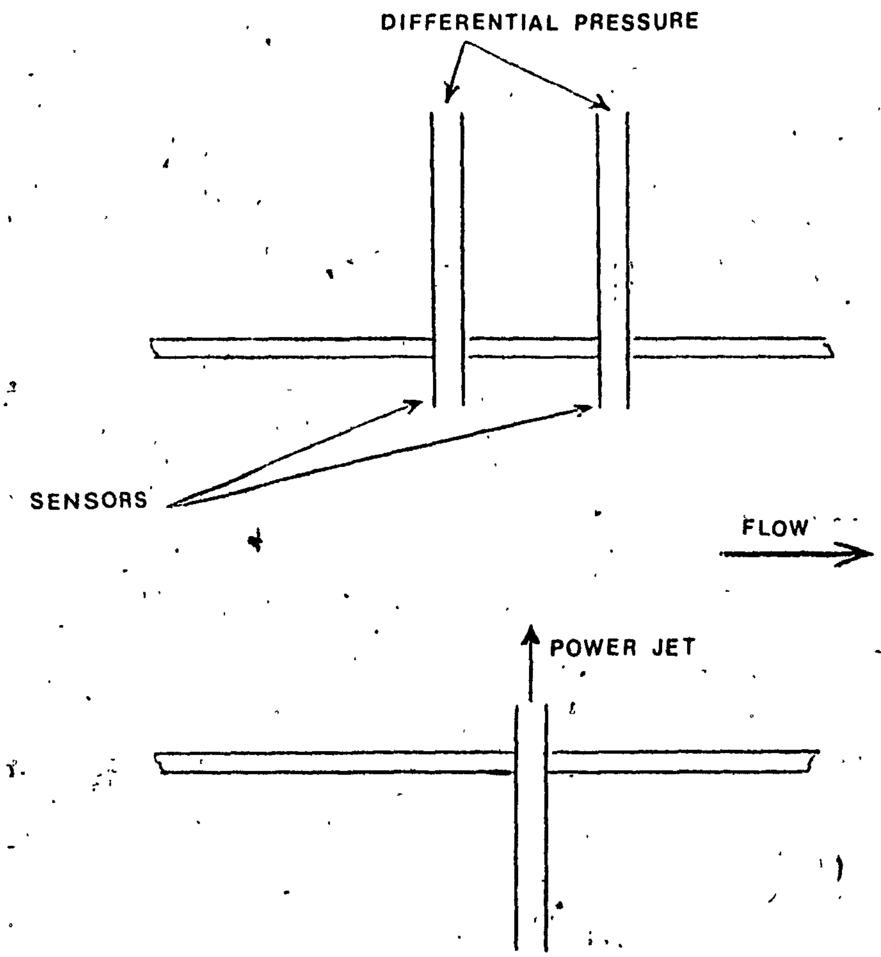


FIG 15 FLUIDIC FLOWMETER – CROSS FLOW TYPE – SCHEMATIC

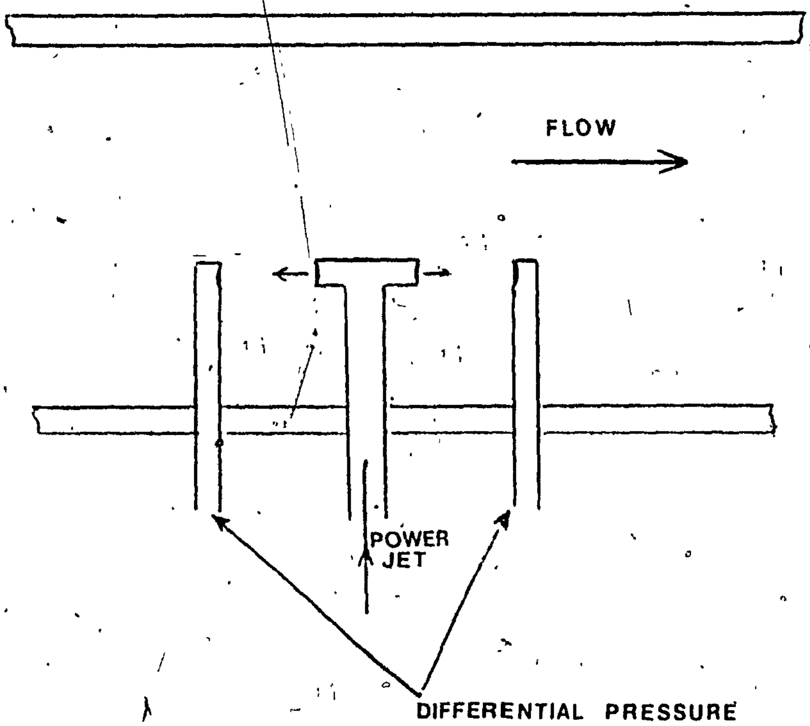
It is shown schematically in figure 15. In the absense of any gas flow, the power jet divides evenly between the output receivers, and the differential pressure transmitter connected across the outputs reads zero.

When gas is flowing in the line, the power jet is deflected downstream, creating an imbalance in the flows entering the two output receivers. Hence a differential pressure results indicating the magnitude of the flow.

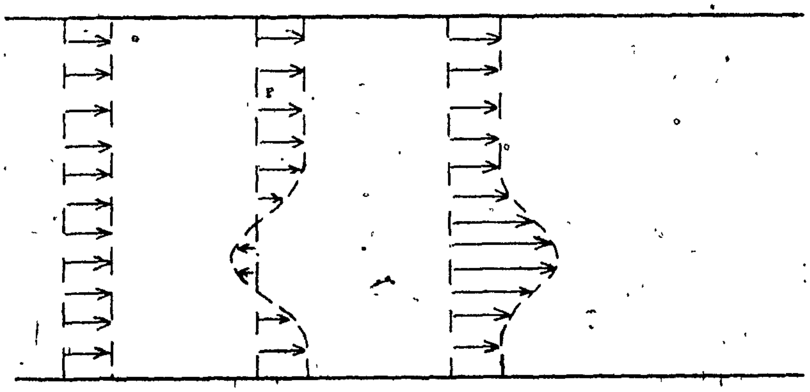
As has been already stated, this device requires a high pressure power source to maintain linearity, and saturates at a gas flow velocity of about 60 ft/sec, making it only marginally suitable for use in heavy water plants, and unsuitable for most other process plants where economic gas velocities are in the order of 100 ft/sec.

The second and less conventional device[18] is a parallel flow sensor operating on the principle of shear interaction. Figure 16(a) shows this device schematically. It uses a dual nozzle power source to direct jets axially upstream and downstream where output receivers are located. These measure the differential pressure resulting from the superposition of the power jet velocity on the free stream velocity. The velocity profiles at the upstream and downstream sensor are shown in figure 16(b).

In spite of the low pressure requirement of the power jet for this parallel flow meter, the differential pressure produced is large enough (0.3 psi at 60 ft/sec. stream velocity) to permit the use



(a) SCHEMATIC DIAGRAM



(b) VELOCITY PROFILES

FIG 16 FLUIDIC FLOWMETER – PARALLEL FLOW TYPE of rugged and conventional instrumentation.

A drawback to these fluidic devices when used for gas flow measurement is the need to use hydrogen sulphide, the process gas, for the power source, or alternatively an inert gas such as nitrogen. Ingress of oxygen to the process is unacceptable since it aggravates the already severe corrosive conditions. An inert gas such as nitrogen could be removed by the process purging system. However, a method of using the pressure of the gas stream itself to provide the power source would be advantageous.

A further avenue of investigation of these devices is their potential for measuring process liquid flows. Since the process liquid is water saturated with hydrogen sulphide, water would be acceptable as the power source in the first stage. An assessment of the total flow of water entering the process this way would be necessary before extending the use of such a device to the second process stage, since degradation of the heavy water by the injected light water might be unacceptable.

The cross flow sensor has demonstrated its ability to measure water flows[19] but the results reported were for low flows below 1 ft/sec. This range would obviously need to be extended for process flow measurement.

CONCLUSION

Of the various flow measurement devices studied in this report, several appear to be worthy of continued investigation for use in heavy water plants. Many have high capital costs, partly due to complex circuitry and instrumentation.

Meters of the cross correlation type appear to offer very broad scope for development. Their cost appears to depend very largely on the equipment used to detect and measure the inhomogeneity or tracer in the flow stream. However, this might be minimized by adopting an artificially injected tracer which could be more readily detected than the naturally occurring inhomogeneities.

The fluidic flow meter (parallel flow type) appears to be the device most worthy of further development for the following reasons:

a) The components are inexpensive.

b) It is an insertion type device, hence one size can be used for all line sizes, and pressure drop of the flowing fluid is minimal.

c) There is no reason why it cannot be developed in forms suitable for liquid and gas flow measurement.

Possible disadvantages are:

a) An external power jet is required which must be compatible with the process or else inert and removable.

b) A differential pressure transmitter is an essential accessory.

c) The device is very sensitive to fluctuations in temperature difference between the flowing fluid and the power jet.

d) The device is very sensitive to misalignment of the jet and sensors to the direction of flow.

A suggested three phase development program to produce a prototype of a commercially acceptable flowmeter is outlined below.

PHASE I The device which was investigated in this report (17) had been applied mainly to the measurement of low velocity gas flows, typically wind measurements. However, its accuracy and linearity extended over a very wide range of velocities, and encompassed the velocity range of gas streams in heavy water plants. Results reported for water flow measurement (19) were at low velocity only (up to 1 ft/sec).

Since it is desirable to design a device, or two separate devices, for liquid and gas applications, effort should initially be devoted to demonstrating the suitability of the technique for liquid flow measurement. This phase of the program should provide an indication of the operating range over which the reading is linear and stable.

PHASE II It is probable that the range of operation of this flow meter and its accuracy and stability over this range are largely dependent on the detail design of the device and on the pressure and flow of the power jet. This phase of the development program should therefore be aimed at optimizing the geometry of the device and the power jet characteristics to obtain maximum accuracy and stability over its operating range. It is probable that different models will result for liquid and gas flows, and possible that better results may be obtained if different designs are used for high and low flows.

Individual parameters to be investigated are:

a) The nozzle profiles

b) The nozzle separations

c) The nozzle diameters and power jet characteristics in relation to the flow rate being measured and the nozzle separations.

d) The geometry of the tubing connections between the nozzles.

Because injection of the power jet into the process fluid is undesirable, the minimum acceptable flow of the power jet should be carefully established, but the nozzle diameters should not be less than ¼" to avoid any danger of plugging.

PHASE III Having established the optimum detail design of the fluidic flowmeter (or several optimum designs for different flow ranges of liquid and gas streams) a prototype commercial flow meter should be designed, manufactured, and tested.

This instrument should be constructed so that all parts in contact with the process fluid are of austenitic stainless steel to resist corrosion. It must be rugged and therefore the two tubes connecting the nozzles to the differential pressure transmitter, and the tube connected to the power jet should be enclosed in a single shroud tube between their point of entry into the fluid stream to the nozzles.

The complete device should be flange mounted to facilitate insertion at a TEE or other suitable pipe connection.

Prior to manufacture, a model with similar inertial characteristics should be tested to ensure that vibration will not occur and prevent successful operation of the device or cause mechanical damage.

A final avenue of investigation additional to the three phases program already described is the possibility of using the process fluid to provide the power jet. This would obviate the need for an additional supply of water, in the case of a liquid flow meter, or inert gas such as nitrogen in the case of a gas flow meter. The pumping, pressurizing, and piping systems for an external power jet fluid may add significantly to the total cost of the installed flow meter, and present the most serious drawback to its commercial success.

The difficulty in attaining this objective lies in boosting the pressure of the process fluid to the higher value required for the power jet. Stagnation pressure can be harnessed to provide the necessary boost, but only if the flow area is reduced at the point where the dynamic pressure is harnessed, so that the available velocity head is increased.

To produce by stagnation the minimum power jet pressure differential of 3 psi required for the gas flow meter the process gas velocity must first be increased from its normal value of 60 ft/sec to a minimum value of 123 ft/sec, which can be achieved without imposing an unacceptable pressure drop on the system

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