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Norske Sivilingeniørers Forening

NORTH SEA FLOW METERING WORKSHOP

Stavanger, 13-15 October 1987

Fiscal Metering Systems for North Sea Oil & Gas
Experience from Purchasing to Start-Up

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FISCAL METERING SYSTEMS FOR NORTH SEA OIL & GAS
EXPERIENCE FROM PURCHASING TO START-UP.

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INTRODUCTION

The experience described in this paper reflects the experience of the authors from being involved in metering systems from different manufacturers both on the mechanical side and on the computer side.

The viewpoints and recommendations given here represent the opinion of the authors and do not necessarily reflect established procedures in their companies.

All viewpoints and recommendations expressed here are, in our opinion general and should be relevant to any manufacturer of metering systems.

The recommendations are aimed at both oil companies and metering equipment manufacturers.

You may ask:

What is so special about a metering system that three lectures are used at this workshop just to discuss its early life from purchase to start up? In fact, a number of people have put forward the question of what is so special about these metering systems. Very often, the question comes from project managers and procurement people in the development project organisation. If they don't get a good answer, they will know most of it at the end of the project:

- Complexity

In spite of the simplicity of the basic principles of measurement, an offshore metering system as a whole may be a complicated package.

- Inadequate standards

In spite of the fact that the design of the system is referred to as being in accordance with API or ISO standards, there are a number of important details not specified in the above standards.

- Approvals

There are a number of "interested parties" to a fiscal metering system. Both law and commercial agreements give rights to these "parties" to approve the metering system. The "parties" having an interest in a fiscal metering system will be several or, in extreme cases, all of the following:

- The buyer (Personell from the project team and also personell from his operating department.)
- NPD (By Norwegian Law and regulations)
- DoE (By international treaty if a "unified" reservoir)
- The Norwegian Directorate of Legal Meteorology (onshore)
- Pipeline operator (By transportation agreement)
- Other "shippers" of hydrocarbons through the same multifield pipeline
- Field partners

- No metering, no production

You will normally not be allowed by NPD to start shipping of hydrocarbons from a field with the metering system faulty or not functioning.

Based on the above factors, it should be evident why careful attention must be paid to the metering system in all phases from purchasing into operation.

STAGES OF A METERING SYSTEM'S LIFE

We may split the process "FROM PURCHASING TO START UP" into 13 stages as tabulated below. This paper give viewpoints, in separate sections, which are relevant to those stages marked by an asterisk. In addition, the two last sections of the paper deals with two further aspects which are: NPD approval and relation between operations department/project team.

1. Technical Specification for Bid Invitation *
2. Evaluation of Bids *
3. Bid Clarification Meetings *
4. Updating Technical Specification
5. Purchase Order
6. "Kick Off Meeting"
7. Fabrication *
8. Factory Acceptance Tests *
9. Preservation *
10. Shipping
11. Commissioning/on-site tests
12. Start *

TECHNICAL SPECIFICATION FOR BID INVITATION

Ideally, this specification should specify all details of the system.

The advantage of writing a "tight" spec. is, of course, that you get exactly what you want. Also, it is much more easy to evaluate the different bids since there will not be any deviation between them, technically. With regard to bid evaluation, it is in particular beneficial to specify make and model of valves, accuracy of computing equipment, criteria for sizing the prover and required lengths of upstream tubing of gas meter runs. These details have great impact on cost. For example, full-bore valves may be twice as expensive as valves with reduced bore.

There are, however, disadvantages of writing a "tight" spec.: Firstly you will not benefit from the manufacturer's ability to optimize the system design and, secondly, you may make errors.

So, it is in our opinion important to request that the manufacturer in his bid also offer options which he considers more optimal and also that any errors in your specification are pointed out.

Also, when writing the technical details of the spec., you should always ask yourself if it would be possible to get what you want by making a functional requirement rather than a purely technical one.

A further point which should be carefully considered is whether or not to include any "specialised sub system" in the specification if the metering system vendor has no particular experience in the relevant technical area. What we have in mind when saying this are equipment like on-line chromatograph, automatic sampling systems etc. These subsystems may, functionally, be part of the fiscal metering but are, technically, very different from the flowmetering system. You may be better off by ordering such items separately, from a specialised company.

EVALUATION OF BIDS

Some viewpoints on the comparison of prices of the different bids:

- It is important that the prices are compared on a common basis. This means that the major items of the system must be of the same quality and price-class. If they are not, the comparison must take into account the additional costs or savings caused by the deviation from the desired quality-level. The major items where quality and price may differ are mainly valves, provers and computersystems.

- The rule of the project procedure is to select the lowest bid which satisfy the technical specification.

This rule implies that a very tight (ideal?) specification has been written and that a very large amount of competent manpower is spent in the evaluation work. If not, it must be borne in mind that the lowest bid may not necessarily be the best. If a very low bid is selected, the manufacturer may have less freedom to implement the unavoidable minor changes of design during the project.

BID CLARIFICATION MEETINGS

No part of the clarification should be delayed till after the order has been issued. Even if the purchase order gets delayed beyond the project's schedule, sufficient time should be used to gain complete clarification of the bids. The advantages of getting a full clarification before the order is issued are evident:

- The buyer is in a better bargaining position in this stage.
- It is cheaper to do changes before design/fabrication has started.
- Even if you take some blows from the project manager because of upsetting the schedule, you will have to fight much harder for any change after the order.

The bid clarifications should always include a page-by-page review of the purchaser's technical specification, which means that the time required is more a matter of days than a matter of hours.

If your spec. was good enough, you may get off a lot easier, though.

FABRICATION

During this stage there will normally be held a series of technical clarification meetings and the buyer will follow up the progress of the fabrication process. We have some viewpoints and recommendations which apply to this.

Supervision of meteorological and operational characteristics

For the oil company, the manufacturer at this stage has a tendency to reveal a second personality. In the previous stages, the metering system was dealt with as an item where metrological qualities and operational characteristics had first priority.

When fabrication starts, the manufacturer gets into another gear where the above qualities are not so important compared to the new priority which is fabrication. From now on, all efforts are used to produce the items from which the system is to be put together. The purchaser may feel that there is little time and resources allocated to check the metrological qualities of the system that is put together.

For the oil companies, this is felt as a significant problem when buying a metering system. The causes and possible solutions to this problem were extensively discussed between the authors of this paper. Our recommendations are as follows:

- The specification and bid clarification should, in many cases, have been better. More and better work should have been done. In particular, the SMDL should include more drawings and documentation so that undesired design details can be detected as soon as possible after the drawing board. (SMDL = Supplier's Master Document List).

- The manufacturer should have a person in his organisation who has the time and competence to perform a continuous supervision of the manufactured items on the basis of metrological and operational characteristics of the full system. This person should have an obligation to make the buyer aware of any unintended consequences of buyer's spec. appearing as the system is put together.

This task can probably not be handled by the manufacturer's project leader since his first priority will, traditionally be to control the progress of fabrication and cost.

The right person to do this will be a competent metering engineer preferably with operational experience. To make sure that the right man and adequate resources are used, it may be beneficial to obtain an agreement on this as a separate item of the scope of work, specifying the name of the person to do the work.

Alternatively, this job might possibly be carried out by an extensive on-site follow up by competent personell from the buyer.

- To give a fast and correct answer to the vendor when a question or a problem arise in relation to metrological and operational characteristics, the buyer must have personell available to reply quickly. If answers or decisions are delayed, the manufacturer has to take a decision on the buyer's behalf to avoid delays in fabrication.
- The following basic rules should be established for the communication between buyer and manufacturer:
 - . Stay on talking terms.
 - . Avoid "ping-pong game" with telexes, instead make agreements verbally and confirm by telex.

- . Have regular formal project meetings with a frequency of, say, once a month.

Problems with Delivery Schedule

In most cases, the delivery schedule for the metering package is critical for a platform project.

Problems with the delivery of metering packages have occurred in the past and we have tried to look into what the oil companies, on their part, can do to minimise the risk of this.

We believe that the following recommendations are particularly relevant for metering systems:

- If/when issuing change orders, always clarify if these have any "schedule impact".
If the schedule is critical, don't issue any such change orders at all.
- Return reviewed drawings and documents to the manufacturer within the agreed time.
- Be aware that software may be a bottleneck. Avoid software functions that are too complicated, too extensive and too non-standard.
- Generally, establish structured and organised communication and working relationship with the vendor.

FACTORY ACCEPTANCE TEST

The factory acceptance test is the take-over test at the manufacturer's plant.

Normally, the completion of this test means that the customer gives his final approval of the metering system. All further work and testing will be outside the fixed price and strict time schedule of the purchase order.

It is therefore important that this test is properly conducted.

For many metering systems in the North Sea this has not been the case. The result has been that serious problems have occurred at start up.

Also, there is a tendency that the "non-fatal" errors remain uncorrected in the systems for years of operation.

By reviewing the problems known to us that has occurred during start up and operation, we have arrived at the following recommendations and afterthoughts for the factory acceptance tests:

- Test all equipment!

At a FAT, the main activity (and problems) are very often concerned with the electronic equipment. Other important factors, such as operability and leak-tightness of orifice fittings, live checks of computers' control of valves etc. are often ignored. Considering how complicated it is to improve any machining of the inside of an orifice fitting when your system has come in operation, it is evident that a check or test of this and equivalent items should never be forgotten at the FAT.

- Allocate sufficient time to FAT!

The main problem when doing a FAT is normally the time that you have available. Make sure that sufficient time has been allocated to FAT in the schedule of the order. You must then take into account the complexity of the system and also the time needed to rig up those computer systems that the metering computers shall communicate with. The most usual reason for insufficient time for the FAT is that the time schedule has been allowed to slip for activities before the FAT.

- Make a detailed test procedure!

You cannot do a good test of a metering system just by improvising. The test must be carefully planned and a detailed procedure must be made in advance of the test. This procedure must describe precisely the method of the tests, equipment that is needed, its accuracy and the acceptance criteria/tolerances. The test procedure may be made either by the buyer or the manufacturer. It is, however, important that it is available for review/approval in ample time before the FAT.

When doing the test, it is important that the procedure is followed and also that it has been allowed time for testing details that you find, when testing, is not included in the procedure.

- Use updated documentation!

Make sure that all drawings and handbooks are updated and complete before the test.

- Prepare thoroughly before the test!

From the buyer's side, an adequate amount of work must be made to get a full overview of the system before the FAT starts. The purchase order and any change orders must be carefully reviewed. The same goes for the manufacturers functional specification.

(The same applies of course, also for the test personell of the manufacturer.)

- Manufacturer must document his own tests!

A major problem at FATs in the past has been that the manufacturer has not been thorough enough in his internal testing before the FAT.

This has, in particular, been the case for the software of the computing system. As a result, a substantial part of the time at FATs has been used to diagnose errors and get them corrected.

It is therefore very important that

- . The manufacturer do a proper test before FAT and
- . The results of this is documented and available to the buyer in ample time before FAT and
- . All test equipment the manufacturer has used is properly described and its calibration documented.

- Test the complete metering system!

A serious shortcoming of the FATs has been that the computing system has been tested with a simulated connection or without a connection at all to the field equipment and to other platform computer systems.

The "working environment" of the system has thus been very simplified when comparing it to the real life situation. This has probably been the largest shortcoming of most FATs in the past.

On the other hand, it may be very time and cost consuming to arrange a FAT where the real working environment is present. We will nevertheless recommend the following:

- . Bring along and test the system with all RTUs and SCADA-systems tied to it. (RTU = Remote Terminal Unit).
- . For oil metering systems, do not make the full system test with simulated outputs/inputs from/to field equipment.
- . For gas metering systems, check very carefully that the valve control signals match the valves and valve sequences required. To the extent that simulated inputs/outputs are used to/from field equipment, see that the simulation panel rigged up with satisfactory potentiometers and proper marking.

Keep discipline!

At the FAT, the buyer (and NPD) have their first full view of the system and its operational details.

In this kind of situation, it is very easy to produce a number of good ideas to improvements to a number of details that seem very easy to change on the spot.

(We are now referring mostly to the software functions.)

It is, however, very important to keep a very disciplined attitude in this respect both because of possible schedule impacts and because of that software changes implemented at the spur of the moment often get you into trouble by having adverse effects on other functions.

PRESERVATION

Normally, after shipping from the manufacturer, the metering system will be inactive for a substantial period before start up. It is necessary to take precautions against corrosion. This can be made by:

- All water after hydrostatic test or flow test must be drained out and the pipework must be thoroughly dried.
- Corrosion is prevented by filling the tubing with nitrogen at a slight overpressure. An adequate bottle supplying nitrogen continuously to the system as overpressure is decreasing, must be part of the shipped package.
- Alternatively, the inside of the tubing may be coated by special methods.
- All delicate parts are taken off the package and shipped/stored separately (Densitymeters, orifice plates).

Experience shows, however, that it is very often a problem to maintain preservation during the storage time.

If the pipework has too many/too large leaks, the nitrogen will have to be topped up at an unacceptable rate (once every 2 - 7 days for a large system). If the pipework is opened for inspection purposes, somebody has to remember to reestablish preservation.

In case of internally coated systems, one is dependent of pipework being properly dried and properly coated.

START

At start up of operation, the system will for the first time be exposed to a real - life working environment. A lot of situations which were not foreseen at the tests may occur. This means that errors may occur.

We can mention some examples known from the past:

- The flowcomputers stopped in situations when flow got small fluctuations.
- The computers did not manage to communicate when they got the full workload of responding to live signals and live PCDA system.
- Valve opening times was longer than programmed in software, error messages occurred all the time.
- Pulse duration for samplers were to short for the sampling system/pneumatic power as installed on the platform.
- Computers stopped because the platform powersupply gave small (within spec.) variations in voltage.
- Etc.

As regards operation of the system, the following is of importance at start up:

- Operators must be well trained.
- The system must have been designed to be simple to operate and easy to understand.
- The system must have an operator's manual. To day there is a tendency that the full functional spec. and operator's manual is combined in the same document. This is not good enough.
- A software engineer from the manufacturer and equipment to correct programs should be present on the platform at start up and during the first days of operation.

RELATION BETWEEN OPERATIONS DEPARTMENT AND PROJECT TEAM

Actually, within an oil company, traditionally there are two "interested parties" to the metering system. These are

- The project team and
- The operations department.

The project team has been organised to operate in a limited period of time and its function is to supervise and cooperate with the engineering contractor who purchases the metering system and handles it until it is installed on the platform.

The operations department is the actual "buyer" of the system and he is the one who will suffer if a bad system is installed.

It is therefore important that the operations department have a significant influence on the metering system from the bid evaluation stage and onwards. With due respect to all project engineers, it must be borne in mind that while the operations department is the one to live with the metering system in operation for a number of years, the project team/engineering contractor are normally through with their job when the system is mechanically complete on the platform and they "get their marks" on the basis of:

- Project costs and
- how well the schedule has been met.

A further aspect of involving the operations department in the process from purchasing to start up, is the transfer of operating experience into the project. In many cases the operations department has gained extensive experience with operation and maintenance of metering systems. Consequently they will be in a position where they may give valuable inputs to the project team/engineering contractor.

NPD APPROVAL OF DESIGN

If we take the NPD gas regulations as a basis, a metering system need the following approvals from NPD before start-up:

- Approval of design (NPD gas metering regul., ch. 5, para 41)
- Approval of system at manufacturer's site
(NPD gas metering regul., ch. 6, para 49)
- Approval of system at area of application (i.e. platform)
(NPD gas metering regul., ch. 6, para 49)

In this paper we will give some recommendations and viewpoints on the first of these approvals, i.e. approval of design. The two other approvals above, and other approvals needed (for procedures, safety etc.) are not dealt with here.

The first paragraph of chapter 5 of the NPD gas metering regulations reads as follows:

"The design of the metering system shall be approved by the Norwegian Petroleum Directorate.

Application for approval of the design of the metering system shall be submitted in a set of documents containing a complete technical description of the system. These documents shall contain the documents specified in this chapter. However, the Norwegian Petroleum Directorate may ask for supplementary informations."

This paragraph give the oil companies the right to apply for a approval of the design of the system at the early design stage, as soon as the required documentation (specified in paragraphs 42-47 of the regulations) is available.

For NPD it means that they have an obligation to approve or disapprove the system design.

It is highly recommended to the oil companies to apply for design approval of their metering system as early as possible in the design phase. At this stage, the costs of changing the design is small. If approval is applied for, and turned down, after the system has been built you may face a disaster both in terms of money and schedule delay.

The most common problem in doing this, is to get the technical documentation that you need for the application at an early stage. This may, however, be solved by including the appropriate requirements in the purchase order of the metering system.

NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

**NORTH SEA FLOW METERING
WORKSHOP**

13 - 15 October 1987

Stavanger Forum, Stavanger

**PURCHASING A FISCAL FLOW METERING STATION
SUPPLIERS POINT OF VIEW**

1.2

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NORTH SEA FLOW METERING WORKSHOP
PURCHASING A FISCAL FLOW METERING STATION
SUPPLIERS POINT OF VIEW

1.0 INTRODUCTION

Today we will hear the views of the purchaser/operator; the Fiscal Authority and the Supplier on the purchase of a Fiscal Flow Metering Station. We will assume that the intention of all the groups is to provide metering systems to the highest quality with regard to flow metering, recognising that price can be an overriding consideration.

This paper will detail the major factors of concern to the supplier, consistent with meeting the common objective.

This will include the following major areas, (i) quotation (ii) specifications (iii) design/engineering (iv) purchasing (v) manufacture (vi) testing (vii) installation/commissioning/service (viii) quality assurance (ix) price/delivery (x) research and development (xi) documentation (xii) areas for improvement.

It should be noted that the experience of our company has been very good working on large fiscal metering systems for Norway and slides 1 to 5 show examples of the end product.

2.0 QUOTATION

- 2.1 The supplier is involved in the project generally when requested to quote and at that stage he would normally be presented with large volumes of the customers specifications. In some instances the converse is the case and a £ 5M job has been bid based on 2 pages of specification.
- 2.2 The suppliers prefer to be involved in projects prior to the presentation of bid documents. This may take the form of discussion of operating parameters, meter sizing and layout, or on a specific material problem. It is of assistance to the supplier, as he is then aware of the background to the request to bid and consequently can make a more intelligent presentation. In addition it would be an advantage to the customer since he can obtain helpful suggestions/calculations etc., while he is at the conceptual stage of designing his plant, based on the suppliers expertise.
- 2.3 Generally the customer wishes the quotation turned round in a very brief period. The supplier understands the need for urgency but he must make a judgement on how to respond based on some of the following restraints (a) the current work load of

those in the estimating section (b) the apparent complexity of the specification (c) the existing work load in the factory (d) the experience of the supplier with the particular customer, i.e. does the supplier get a fair share of the jobs he normally bids to that particular customer (e) knowledge of the specific job.

- 2.4 When deciding how to respond, it would be helpful, if the customer highlighted, in his request to bid documents, all the major deviations from international specifications, e.g. unusual material requirements, specific documentation or inspection needs, unusual equipment needs, etc. Reviewing specifications should not be similar to background reading for Mastermind where the competitors chosen subject is "Firm X's Specification Sections AA to Sections ZZ inclusive" with any passes, resulting in the supplier losing an order or costing the supplier many thousand pounds in the course of the project. Issuing specifications should not be a method of catching out unsuspecting suppliers but should be a method of accurately informing all the potential suppliers such that they can produce a precise, intelligent quote, on time
- 2.5 It should be borne in mind that all suppliers get a small percentage of the jobs for which they bid and

large metering stations involve the supplier in considerable expense which is never recovered if he is unsuccessful with his bid. This means that the supplier has to limit the time he spends reviewing specifications and the experienced estimator looks for exceptions to the norm.

2.6 Perhaps the customer should consider paying the suppliers who quote, but do not get the job. This would ensure improved quotations and would stop suppliers feeling that in some instances they are simply making up one of the three quotes required by the Purchasing Manager.

3.0 SPECIFICATIONS

These can be divided into four main headings:

- (i) International Specifications
- (ii) National Specifications
- (iii) Fiscal Authority Requirements
- (iv) Customers Specifications.

3.1 INTERNATIONAL SPECIFICATIONS

These generally present least problem to the experienced/reputable supplier. The specifications would generally cover such items as metering (e.g. ISO 5167 for Orifice Metering and API Chapter 4 for Crude Oil Metering); materials, valves, instruments, drawings, cables, safety,

quality assurance etc. Problems may arise if there is a recent revision of such a specification and in such a case it would be helpful if the customer drew attention to items he is aware of which have changed and specifies the Standard by revision number and date.

3.2 NATIONAL SPECIFICATIONS

In the U.K. these are the British Standards and the Institute of Petroleum Codes, and in Norway, the N.S. Standards apply. For companies operating in international markets it is essential that they are familiar with the National Standards in the country to which the equipment is to be supplied, but this takes time. It is helpful however, if the customer can highlight variations between their own National standards and the International ones. Daniel normally find that the Norwegian companies do a very good job in this respect. For example when N.S. 5801 was introduced, Statoil personnel spent considerable time and money to ensure that Daniel were aware of its implications.

To assist international trade the use of International Specifications is always to be preferred. It is unfortunate when the impression is created that National Specifications are being used by a country to legitimise a trade embargo.

3.3 FISCAL AUTHORITY REQUIREMENTS

In the case of flow metering stations for the North Sea we are normally considering one or a combination of the following, the Norwegian Petroleum Directorate (N.P.D.), the Direktoratet for Maleteknikk, and the Department of Energy (D. of E.) requirements all of which are different in certain aspects. We find the N.P.D. regulations the most comprehensive and most in keeping with International Standards on flow metering. As suppliers we appreciate the opportunity to comment on any revisions to these documents, it not only allows intelligent discussion but it also permits the supplier to prepare for any changes.

3.4 CUSTOMERS SPECIFICATIONS

These are generally the most controversial specifications and the ones most likely to lead to confusion. Obviously the customer has to prepare project specific specifications but it would be helpful if specifications for general equipment that have survived the test of time are not subject to continuous specification updating. From this point of view the specifications of the long standing oil companies have much to commend them. When a contract is awarded the customer

should not present the supplier with new revisions of his specification. If he does, he should expect to reimburse the supplier for the time involved reviewing the specification in addition to cost and time involved in implementing the changes.

4.0 DESIGN - ENGINEERING

4.1 This is the most critical aspect in the production of a quality fiscal metering station. If this work is not done precisely and accurately it may well be impossible to rectify the situation at a later stage, e.g. only a limited space may be made available on a platform. At this stage corrections can be made by use of Snowpake or a rubber, whereas by the time equipment is fabricated, burning torches and welding rods are necessary and this is an expensive route to rectification.

4.2 The following prerequisites are essential for the design of a fiscal metering station.

- a) A clearly defined specification giving precise details of fluid to be metered and physical properties at operating condition.
- b) Operating conditions - flow range, pressure, temperature (normal and extremes properly identified).

- c) Standard Conditions for temperature and pressure.
- d) Clear definition of any limitations on Station size and weight for both the skid and for the panel.
- e) Interface with surrounding equipment e.g.
 - (i) pump curves for flow control
 - (ii) imposed stress from adjacent pipework
 - (iii) telemetry requirements
 - (iv) print out format etc.
- f) Delivery requirements.
- g) Drawings required (including standards) calculations etc.
- h) Competent mechanical, electronic and software engineering group with experience in the design of large fiscal metering packages.

4.3 The design engineers should work with the client from the receipt of the order through to delivery and if necessary to site. As most of these systems are unique, the engineer must design precisely to the customers requirements.

Realistically, the customer has not always precisely defined his needs prior to the award of contract and the good supplier should adapt to the customers needs as the project proceeds. This imposes certain restraints on both parties involved, namely (a) the customer must be prepared

to recognise the fact that changes are required to be paid for (b) the supplier must not regard change orders as opening Pandora's Box to increase profitability.

5.0 PURCHASING

5.1 As in the case in design engineering and in all the disciplines, Purchasing has to conform to the requirements of Quality Assurance Standard N.S.5801 and/or B.S. 5750 Part 1.

This ensures that the Purchasing Group use only approved suppliers and that there is a checking procedure so that the purchase request documents are checked and countersigned. The customers specifications are then assured of being adhered to, with regards to such items as materials, accuracy, non-destructive testing, certification, quality assurance, spares, documentation etc.

5.2 However, there is an increasing trend by the customer to give recommended suppliers. This is understandable, as the customer will get the identical equipment. ensuring uniformity on site with regards to spares, manuals, etc. System suppliers will assume that if the customer has recommended a supplier than it has been audited by the customer. In this instance our company would not carry out a quality audit.

The disadvantage of this route to the supplier is that he may be using a supplier whose equipment is not totally familiar.

6.0 MANUFACTURING

6.1 In order to manufacture a fiscal metering station the resources of (i) space (ii) machines and (iii) competent labour force must be available. It is also desirable that the manufacturing unit is sited in close proximity to all the other disciplines, e.g. purchasing and engineering to maximise communications.

6.2 The bulk of the manhours used on a metering system are generally expended in the manufacturing area. This means that the personnel must be adequately trained, work to clear work instructions/drawings, have proper tools for the job and be carefully supervised.

The personnel must carry appropriate qualifications, e.g. coded welders, qualified radiographers and N.D.T. personnel, etc.

6.3 In addition to producing a quality product, manufacturing are asked to work to very tight time schedules. This constant pressure is not always the customers fault (as most suppliers would maintain). It can be a combination of a number of factors many of which are under the suppliers

control. Such factors are (a) agreeing to a tight delivery since at the negotiation stage the Purchasing Manager has indicated that the competitors have promised a much better delivery. The customer asks for as tight a time schedule as possible in the hope that his actual required date can be maintained. This can lead to situation where the management push hard to meet an agreed date and the unit then lies around the factory for months. This can affect the attitude to the next order for that particular customer and the workforce may conclude that management have pushed them hard for no apparently good reason.

(b) the sub suppliers may state at the time of a budget request that a certain delivery can be achieved. Then when a formal order is placed with all the specifications attached, the delivery date dramatically extends. This can result in the manufacturing personnel having to make up for this lost time. This is a specific area where the suppliers experience can be useful.

(c) internal work loading in the plant can give the manufacturing unit a major problem. The sales department make a projection of forward loading but often order placements go back and orders which were confidently predicted do not materialise.

It makes it difficult for the supplier to plan the manpower requirements in advance in these circumstances. No company likes to have the reputation of a 'hire and fire' company, but in the case of manufacturing large systems, it has become necessary to try and maintain a good professional core and to use temporary labour to deal with peaks.

The oil/gas companies could assist the suppliers by giving as realistic forward projections of projects as is possible.

It is incumbent on the supplier to forward plan his work loading such that all the work undertaken will have the manpower available to meet the delivery dates promised.

Currently we have an ideal example in our plant where the oil company came early to us and placed an order for a duplicate of a large metering package. The oil company did not ask for a tight delivery schedule and consequently we are able to fit this order into the troughs which invariably ripple through from engineering, to purchasing, to manufacturing/quality control, to testing and then shipping.

Having had this help from the client the suppliers are under an increased obligation to produce quality products on time.

6.4 Manufacturing must continually look at mechanical aids to increase efficiency. There are always new machines and techniques flooding the market but in light to heavy mechanical engineering these machines are never inexpensive. A balanced judgement has to be made between high capital expenditure and reduced operating costs. This is never an easy decision with uncertain future orders and accountants continually examining short term profitability.

Automatic welding techniques, N.C. machines etc., are areas already giving valuable returns in a number of companies. Automatic techniques for termination, cabling etc., need to be examined.

6.5 The use of Computer Aided Manufacturing techniques for shop loading and machine control will make ever increasing impact in manufacturing premises in the future.

7.0 TESTING

7.1 One advantage in purchasing a metering system as a single unit is that it can be tried and tested before being installed. This gives a degree of confidence when the unit is installed, which would not be the case if individual items were purchased and put together in a field location. I am sure that there are a number of customers who will

highlight deficiencies which arose when systems were delivered to site. Whilst this could be extremely frustrating it substantiates the general argument for buying a tested system where all of a suppliers experts are available to solve any problems which are found. Think how much worse it would be if the system had not been tested; and the problem had to be resolved on site.

7.2 Items used on the systems such as valves, meters, instruments, transducers etc., should be tested at the sub-supplier before installing in to the metering system. This puts the responsibility for supplying tried and tested components onto the manufacture of the components.

7.3 When it comes to testing components and the system in the suppliers factory there can be differences in opinion as to the scope of these tests. The supplier must convince the customer that he is getting a system which will operate in accordance with the customers specification. It is not possible to provide 100% confidence in the system as the supplier cannot reproduce what will happen in operation, e.g. no gas available for gas flow test; no oil for testing; communications with other instruments/computers are limited, etc. etc. In addition, testing at the suppliers plant is not

an excuse for unlimited experimentation by the customer. This would only be possible if the details of the experiments were discussed at an early stage in the project and the delivery and cost implications were agreed upon. The supplier is under a great deal of pressure to get the equipment out in time and within budget and additional testing time means that these objectives cannot be met. The customer is not always aware of the pressure being applied internally to meet delivery even without expeditors etc., from the customer. Every day one of these large systems is late delays payment, and consequently the supplier has a lot of money paid out with little return until delivery is made.

The conclusion is 'Test by all means, but keep the tests as meaningful as possible over a defined period of time'. The extent of testing must be defined in a test schedule at the award of contract.

8.0 INSTALLATION; COMMISSIONING; SERVICE

8.1 There is little point in providing a well tried and tested system if it is installed poorly, and badly commissioned. What can be done to avoid such pitfalls? There is a wide spectrum of approaches, none of which seems to be ideal. These range from

the customer having a contractor buy and engineer the equipment and then hands it over to the operating group, who have never seen the unit but are expected to install and operate it.

At the other extreme is the oil company which leaves everything to the supply company and expects the supplier to take all the responsibility for supervising installation and commissioning and thereafter servicing the unit.

In an ideal world, the oil company has an operating group which, co-ordinating with the supplier, would have the expertise and the time to engineer the new system exactly as they will require it. They would oversee the supplier, follow the installation, commissioning, and be being able to conduct their own ongoing servicing. This ideal, in Daniel experience, is seldom achieved since such a multi-disciplined team is not available, as it is extremely difficult to release operations personnel for front-end engineering work. Conversely most front-end engineers do not have the experience or the time for commissioning or servicing.

The suppliers supply back-up support for their systems, but there is a difficulty for the supplier in knowing what extent to retain manpower for this aspect of the work. There is a wide variety of

approaches which the customer can choose to take and this variety means there is no definition for the supplier in deciding manpower level. Our company offers a long term servicing contract. Many companies choose not to avail themselves of this. The buyer should not then expect the same level of instant back-up support as the company which has entered into a long term agreement - the supplier simply cannot afford to have manpower waiting for a telephone call which may never occur. The bigger the supplier, the easier it is to spare a qualified person for an urgent call, than it is for a small company.

The suppliers would like to have a situation where either the customer is capable of taking care of most contingencies which arises after the tested unit leaves the factory or (more realistically) the buyer and the supplier reach a long term agreement such that the supplier can have the personnel available to cope with any unforeseen problems.

9.0 QUALITY ASSURANCE

9.1 As one who has earned his living working in Quality Control/Quality Assurance for the last 18 years, my opinion is not exactly unbiased. I am totally committed to the pursuit of quality. The efforts

being made both sides of the North Sea to produce quality products seems to be a major step in the right direction particularly over the last five years. I refrained from saying a 'major step forward' since in Scotland at least, it seems to be simply trying to return to the situation prior to the last world war when 'Made in Scotland' was synonymous with a quality product.

9.2 It seems to me that the advent of B.S. 5750 Part 1 and N.S. 5801 has elevated the quality philosophy to its rightful position in our industrial thinking. The paper work associated with it can be a daunting prospect and in some instances overdone, but we must look at the positive side of quality assurance and accept minor irritants.

9.3 When I examine what I mean by quality, it seems to me that 'Fit for the purpose' is a useful guide and it disturbs me when Inspectors give Quality Assurance a bad name by dwelling on certain minutia of specifications without looking at the overall requirements. Unfortunately this approach gives Production and Accountants a bad impression of Quality personnel which can be counter productive in achieving the desired results.

9.4 To be controversial, it seems to me that the Norwegian approach to the introduction of Quality

Assurance has been much more effective than the U.K. approach. As an outsider I have the impression that in Norway the push on Quality has come from governmental level (as is the case in the U.K.) The Norwegians have then imposed this on the major oil companies who have in turn, passed the requirement onto the sub supplier. Thus pressure is made from the top right through to the several levels of industrial companies.

This results in reduced requirement for D.N.V or Lloyds inspection and we can state, that there is no deterioration in quality when there is no outside inspection.

In the U.K. the procedure has been to introduce a national accreditation scheme to B.S. 5750 which is administered primarily by Lloyds and B.S.I. Unfortunately this had just been introduced when the major oil companies introduced QUASCO requirements and consequently accreditation offers little attraction. Thus the opportunity to introduce a nationwide approach with teeth has been lost. This means that in the U.K., we have some jobs with third part inspection and others without.

10.0 PRICE AND DELIVERY

10.1 The price of a metering station should simply reflect the specification. As metering engineers

we are often surprised how parsimonious major companies can be to metering. This unit which can give so much information as well as being the cash register for the operation is treated to space and price cutting which is unbelievable. It is like running a beautifully designed and planned supermarket and asking those on the cash desk to work with an abacus. This can best be illustrated by examining an Orifice Gas Metering Station made to I.S.O 5167. The upstream and downstream lengths given in Table 3 are for minimum lengths. Does anybody design with longer lengths to give more confidence in the results? Not likely!! It is not just the purchaser who can be at fault in this instance. The supplier in his effort to win the order and to be as competitive as possible offers the minimum within the interpretation of the specification. This can only be overcome by the customer specifying or asking what he requires for accurate metering and paying a price accordingly.

10.2 Previously some suppliers had the reputation of being 'Mr. Extra'. The price was squeezed at purchase order stage and the supplier endeavoured to make their profit by calling everything an extra during the course of a job. Those days are gone! The specifications and contract details are now so

tight that it is virtually impossible for the sub-supplier to claim any extras unless there is a very genuine, documented change in the scope of the contract. In extreme cases the customer can use the contract in an attempt to obtain much that he is not going to pay for. Fortunately there are not too many of these people about.

10.3 A very tight time schedule is not conducive to efficient working in the suppliers unit, unless it is a repeat order. If the buyer can see no way to have a reasonable delivery time the supplier would prefer to be involved in discussion as soon as possible and some intent shown to permit long lead items to be bought.

10.4 What can be done to reduce price and improve the delivery of large metering stations? Apart from reducing all the specifications to a minimum which may lead to an inferior metering station our experience is that a repeat of a previously constructed station is the best technique to reduce time and cost. This is due to the fact that design and draughting can be minimised. The purchasing time can be greatly reduced and manufacturing time can be minimised since previous snags and problems can be avoided.

When a metering station is being considered by an

oil company they should approach reputable suppliers and ask if they had supplied a station to cover a similar set of conditions? The supplier could then supply sufficient information for the customer to decide if the package offered met their requirements. This approach would result in the customer involving the metering companies at an early stage but could well reduce the purchasers own engineering and purchasing time.

10.5 Other areas of price reduction are continually being sought. Different types of meters are being investigated which may not require the same length of upstream and downstream pipe lengths. The search for a small volume prover comparable in performance with a conventional prover continues. Alternative materials can be considered but currently it would appear that the alternatives would add to the delivery due to insufficient supply of such materials.

11. RESEARCH AND DEVELOPMENT

11.1 Should Research and Development into new products be the work of the supplier, the oil company or separate research organisations? As a general view all of these bodies are involved in research and development. This does not mean that they should

carry out their research and development in isolation.

11.2 As the oil and gas companies have the primary source of income and are much larger groups than the manufacturers and the smaller engineering shops, it is my opinion that they should be the prime motivators in research and development, as they have been in the initial development of the prover systems.

This does not mean that they should do the research by themselves but undertake joint ventures where they make the lion's share of the payment.

Why the oil companies? Apart from the financial situation I believe they have the facilities available to carry out the research. For example, only gas companies can undertake work of any great significance on natural gas and companies like British Gas and Gasunie have excellent facilities to undertake test work. Similarly there are few facilities available to test liquified gases and development work on these products would ideally be done jointly in the facilities run by the major oil and gas companies.

11.3 An alternative to this approach is to have large centralised government facilities, such as the National Engineering Laboratories or the National

Bureau of Standards, doing basic research with final field testing done as outlined above. Government facilities certainly play a vital role in initiating new ideas, in testing equipment and developing engineering fundamentals. They also play a vital role in encouraging joint ventures e.g. N.E.L. has undertaken a project to study the effect of edge variations on the orifice and a group of oil and gas companies and suppliers have combined to fund and advise in this work.

11.4 Of course the suppliers do much original work on their own. Where would Daniel be without the original inventive genius of Mr Daniel and his orifice fitting or the Waugh Prover without Mr Waugh's work. The liquid turbine meter, as generally used today, was based on the original meter developed by Mr Potter. Everyone could think of such an example.

I believe that the suppliers must be a source of research and development. However, this costs money and there may be a very long period before there is any return for such an outlay. Where can this cost be paid from? The supplier generally has no natural product such as oil or gas to sell and his source of income is limited to the profit made selling his metering systems to the oil and gas

companies. He is competing with a variety of companies, some of which do no research at all. Consequently if research and development is to be undertaken then there must be sufficient profit in the sale of the metering equipment to cover research cost. Over recent years with costs pruned to a minimum by the suppliers in response to the market demand there is little to spare for research and development and suppliers are forced to closely examine the case for financial outlay in this area. Again, for this reason, I would make the plea for more joint ventures to ensure that meaningful research and development continues on as wide a basis as possible. Remember no single group is the holder of all knowledge in the measurement field.

12. DOCUMENTATION

12.1 Over ten years work in this industry there has been an exponential rise in the amount of paper produced by the supplier of metering equipment. Quotations are more and more extensive. The customer demands to review more and more documents and drawings and these pass back and forth being amended, revised, updated, finalised, reviewed, audited, as built, as constructed and so on and so forth. It seems to be an ever growing game.

Does it produce a better system? Perhaps, since mistakes can be made, and more heads looking at something will surely eliminate many errors but I wonder if most of those errors would not have been identified and corrected by knowledgeable suppliers or oil company personnel before the equipment left the suppliers.

What happens also to the many copies (6 to 12) of certificates supplied? Could one copy not simply be kept in a central location along with a microfilm copy?

12.2 A plea from the supplier would be "Please Mr Oil or Gas Company could you devote some of your resources to identifying means of reducing any unnecessary paper being used". Computers do not seem to be the answer since more paper seems to be required to have the information in such a manner that it can be fed into the computer. Again the computer spews out more and more paper.

12.3 The communications now available in metering have been one of the areas of quite extraordinary development over the last decade. The round differential pressure chart has long disappeared and young engineers are unfamiliar with a planimeter.

Results from a single meter can be fed almost

immediately to central processing areas many kilometres away without one piece of paper being produced or handled.

13. AREAS FOR IMPROVEMENT

13.1 As we are considering the supply of a Fiscal Metering Station let us conclude by a supplier's summary of areas for improvement. Firstly let us consider equipment and then procedural improvements.

13.2 Equipment improvements in metering are now becoming evident. The search for a mass measurement rather than that of a volume has seen the Coriolis meter now reach the market place and it will be interesting to see just how large in size it can become and be a viable alternative. The promise of the Ultrasonic meter to finally provide a meaningful alternative to the orifice meter for gas measurement is an exciting development.

The small volume prover developments have brought a breath of fresh thinking into the whole field of meter calibration. Provided the basic fact that, "the objective of the prover is to calibrate the meter" is not lost sight of then there is going to be much more exciting features in this area.

Much still has to be done in the area of

instrumentation and in line densitometers, "smart" transmitters, in-line gas chromatographs are encouraging moves.

What about a reduction in perhaps the heaviest part of the metering station? Namely the valves and actuators. There seems to be an area here requiring much development work.

3.3 What has been called procedural improvements for the supplier would include many of the items mentioned previously i.e.

- i Use international standards wherever possible
- ii Involve the supplier as early as possible in a project.
- iii Consider the use of a previously designed system from a specific supplier
- iv Pay companies for quoting major systems
- v Continue to develop the Q.A. philosophy and encourage Inspectors to have an appreciation greater than the minutia of a specification.
- vi Do not squeeze price to the extent that good metering is barely achieved.
- vii Do not ask for unrealistic deliveries when these often are not essential.
- viii Let there be more joint ventures in research and development.
- ix Leave the Norwegian forests in place and reduce the volume of paperwork.

NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

**NORTH SEA FLOW METERING
WORKSHOP**

13 - 15 October 1987

Stavanger Forum, Stavanger

BUYING AND INSTALLING A METERING STATION

1.3

Lecturer: Senior Engineer Steinar Fosse,
Norwegian Petroleum Directorate - Norway

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- BUYING AND INSTALLING A METERING STATION.
 - FISCAL AUTHORITIES ROLE IN THIS PROCESS.
-

INTRODUCTION

A Guideline for the application of approval of the design, testing and installation of a metering station according to the Norwegian Petroleum Directorate`s (NPD`s) regulation is given in fig. 1.

The first contact between the licensee and the NPD metering department will be when the plan for development and operation of Petroleum deposits is sent to NPD. Paragraph 15 in the Regulations supplementing the act pertaining to Petroleum activities is stating that a general description to be given of installations and equipment which are planned to be installed, among other things metering facilities.

Paragraph 19 in the same regulation is giving another broad statement concerning the metering of petroleum products.
(Fig. 2)

The more detailed description of the NPD requirements is given in our own regulation for fiscal measurement of oil and gas.

The documentation NPD requires is given in (Fig. 3.) This paragraph is laying the responsibility of submitting correct documentation on the licensee. This could look like a simple way for NPD to put everything on the shoulder`s of the licensee. From a theoretical point of view that is perfectly correct. In the real world however NPD has experienced that to obtain a satisfactory results it is necessary to have close cooperation between NPD and the project team to obtain an optimum result. (For NPD that means a technical excellent solution, for the project team

it means a smooth project progress and to avoid extra work
(cost) due to late implementation of NPD requirements.)

2. DESIGN APPROVAL OF THE METERING SYSTEM

Chapter V in the NPD regulations is dedicated directly to this subject. Paragraph 31 (41) (Fig. 4).

I will draw the essence out of the five relevant paragraphs 32, 37 (43 - 47) to focus on the documentation NPD regard as vital at this stage Fig. 5 and 6 are visualizing this.

It has been occasions over the past years where the licencees have not received the necessary approval from NPD at an early stage of the project. Due to this, major changes had to be implemented to the metering packages. This has caused unnecessary negative vibrations between the licencee and NPD in addition to the extra cost and inconvenience to the project.

3. TESTING, CALIBRATION AND CONTROL OF THE METERING SYSTEM BEFORE START UP

Chapter VI in the NPD regulation is dealing with this aspect. Fig. 7 is giving paragraph 39 (49).

The tests NPD normally witness on a gas metering system are given in fig. 8, and for an oil metering system is fig. 9 giving the same.

4. RECOMMENDATION

The NPD advice to the licencees is that they should stick to the flow sheet shown in viewgraph 1 when they are in the process of buying and installing a fiscal metering station for Norwegian waters.

A vital item which we sometimes have experienced as a bottleneck is the communication.

From our point of view the licencee should rather inform the fiscal authorities too much than the opposite.

5. REFERENCES

1. Regulations supplementing the act pertaining to petroleum activities. (1985)
2. Regulation for fiscal measurement of gas produced in interval waters, in Norwegian terretorial waters and in the Norwegian Continental shelf which is subject to Norwegian sovereignty. (1984)
3. Regulation for fiscal measurement of oil produced in internal waters, in Norwegian terretorial waters and in the Norwegian Continental shelf which is subject to Norwegian sovereignty. (1984)

Fig. 1

FLOW SHEET SHOWING THE VARIOUS STAGES IN NPD'S ACCEPTANCE/APPROVAL ROUTINE FOR A METERING STATION

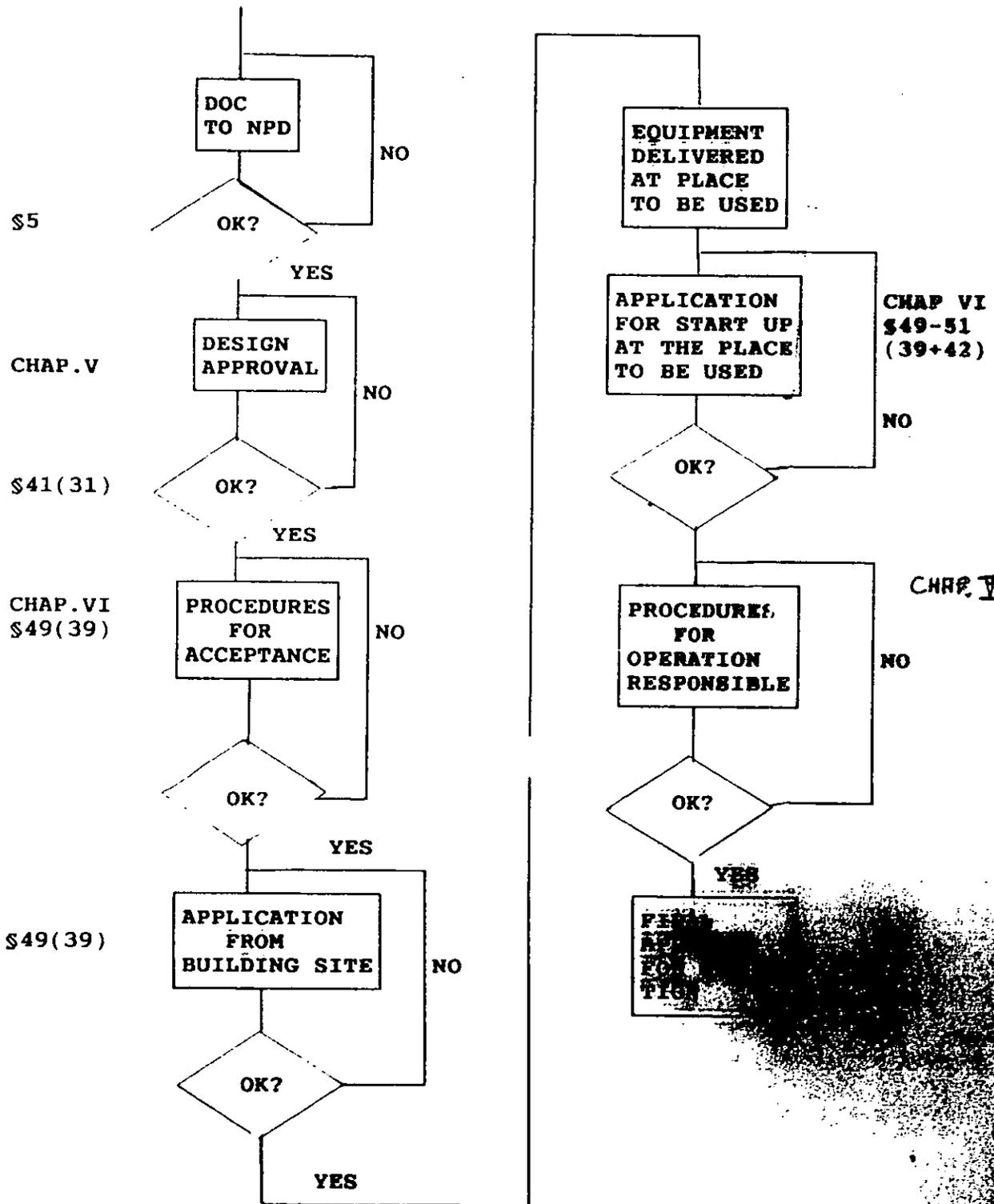


Fig. 2

Section 19

METERING ETC. OF PETROLEUM PRODUCED

THE LICENCEE SHALL METER AND ANALYZE PETROLEUM PRODUCED IN ACCORDANCE WITH GENERALLY ACCEPTED PROCEDURES. THE EQUIPMENT AND PROCEDURES MUST BE APPROVED BY NORWEGIAN PETROLEUM DIRECTORATE.

FIG. 3

SECTION 5

CONTROL AND DOCUMENTATION

BEFORE THE LICENCEE OBTAINS AN APPROVAL IN ACCORDANCE WITH CHAPTERS V, VI & VII, THE FORMER SHOULD SEE TO THAT THE DOCUMENTATION REQUIRED BY THE NORWEGIAN PETROLEUM DIRECTORATE IS IN ACCORDANCE WITH THE REQUIREMENTS STIPULATED IN THIS REGULATION.

FIG. 4

SECTION 31 (41)

DESIGN APPROVAL OF THE METERING SYSTEM

THE DESIGN OF THE METERING SYSTEM SHALL BE APPROVED BY THE NORWEGIAN PETROLEUM DIRECTORATE.

APPLICATION FOR APPROVAL OF THE DESIGN OF THE METERING SYSTEM SHALL BE SUBMITTED IN A SET OF DOCUMENTS CONTAINING A COMPLETE TECHNICAL DESCRIPTION OF THE SYSTEM. THESE DOCUMENTS SHALL CONTAIN THE DOCUMENTS SPECIFIED IN THIS CHAPTER.

FIG. 5

NPД REQUIRE THE LICENCEE TO CONFIRM THAT THE
METERING STATION WILL BE BUILT ACCORDING TO THE NPД
REGULATION.

FIG. 6

1. P & ID (TYPICAL)
2. LOOP DIAGRAM (TYPICAL) ONE FOR EACH SIGNAL TYPE.
3. GENERAL ARRANGEMENT DRAWING. ISOMETRIC SHOWING MAJOR DIMENSIONS, INSTRUMENT LOCATIONS ETC.
4. SIZING CALCULATIONS.
 1. SET TO BE SUPPLIED FOR VERIFICATION OF METHOD.
5. BLOCK DIAGRAM FOR SIGNAL FLOW BETWEEN INSTRUMENTATION AND COMPUTER.

FIG. 7

SECTION 39

ARRANGEMENTS AND PROCEDURES

UNLESS SPECIFIED IN EACH PARAGRAPH, THE CONTROLS AS DESCRIBED IN THIS CHAPTER SHALL BE CARRIED OUT IN THE FOLLOWING ORDER.

- A) BEFORE THE METERING SYSTEM LEAVES THE BUILDING SITE.
- B) AFTER INSTALLATION AT THE PLACE TO BE USED IMMEDIATELY BEFORE START UP.

THE LICENCEE SHALL WORK OUT AND FORWARD TO NPD DETAILED CONTROL PROCEDURES ACCORDING TO THE REQUIREMENTS GIVEN IN THIS CHAPTER. THE NPD SHALL HAVE THE OPPORTUNITY TO BE PRESENT AND WITNESS THE CONTROLS EITHER COMPLETELY OR PARTLY NOTICE ABOUT THE POINT OF TIME FOR THE CONTROLS SHALL BE GIVEN NPD AT LEAST 3 WEEKS IN ADVANCE.

THE METERING SYSTEM SHALL BE APPROVED BY THE NPD BEFORE IT LEAVES THE BUILDING SITE AND BEFORE IT IS PUT IN OPERATION IN THE AREA OF APPLICATION.

FIG. 8

TESTS FOR A GAS METERING STATION WHICH NPD NORMALLY
PARTICIPATE IN

1. MEASUREMENT OF GAS METERING PIPES
2. CHECK OF MECHANICAL/INSTRUMENTPART
3. CHECK OF COMPUTERPART
4. F.A.T. FULL FUNCTIONAL CHECK

TESTS TO BE DONE BOTH ON BUILDING SITE AND OFFSHORE,
BEFORE START UP.

FIG. 9

TESTS FOR AN OIL METERING STATION WHICH NPD NORMALLY PARTICIPATE IN

1. CHECK OF TURBINE METERS
2. CHECK OF MECHANICAL/INSTRUMENT PART
3. CHECK OF COMPUTER PART
4. CALIBRATION OF PROVER
5. F.A.T. FULL FUNCTIONAL CHECK

TESTS TO BE DONE BOTH ON BUILDING SITE AND BEFORE START UP.

PITFALLS

- 1 - Project Engineer's knowledge in fiscal metering is insufficient
- 2 - Project interest in preservation of packages is not high enough
- 3 - Operating personnel is involved at a too late stage
- 4 - Progress is important. Short cuts are therefore done, this leads to failing tests.
Internal tests are not done.

NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

**NORTH SEA FLOW METERING
WORKSHOP**

13 - 15 October 1987

Stavanger Forum, Stavanger

**DESIGN AND SUGGESTIONS TO REDUCE THE VOS EFFECT FOR GAS
DENSITY MEASUREMENT**

2.2

Lecturer: Project Engineer K. Leibe,
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Northsea Flowmetering Workshop

Design and suggestions to reduce the VoS effect for gas density measurement

Summary

The requirements on readout accuracy of gas densitometers have been increased during the last few years. It is desirable to gain an accuracy of field instruments close to that of the lab standards. Different ways direct to that target like modifications and changes in the instrument's design or by using additional mathematical equations based on the velocity of sound offset model.

1. Introduction to Bopp & Reuther Densitometers type DIMB 104.2.

Applicable field instruments for gas density measurement were introduced in the 60's. Different types were based on different working principles. Finally the most successful instruments with highest accuracy use a vibrating sensor. These sensors are operated at their resonance frequencies where a certain amount of energy is introduced into the vibration system only to overcome the friction. The frequency itself depends on fix parameters of the vibrator like mass, shape, elasticity of material and on the density next to the sensor. Usually the sensor is exposed to the gas and the design is in a way a maximum of surrounding gas is effected by the vibrating element to gain highest resolution. (1)

If the sensor is operated at vaccum conditions there is no reaction of a gas and the sensor may vibrate at its' base frequency. Now the sensor is exposed to a gas of a certain density, so it has to move an additional mass and the resonance frequency will drop. (2)

If the sensor is a tuning fork type the fundamental equation that describes the relation of the frequency versus density is:

$$f = C \sqrt{\frac{E}{\rho_{st} + K_1 \rho_G}} \quad \text{where } f = \text{frequency}$$

E = elasticity of sensor material
 ρ_{st} = density of sensor material
 ρ_G = density of gas
C, K_1 = coefficients

As far as the computer receives the frequency and may calculate the density the new equation is:

$$\rho_G = K \left(\left(\frac{B}{f} \right)^2 - 1 \right) \quad \text{where } K, B = \text{coefficients}$$

In the earlier generation of our Bopp & Reuther computers this equation was established. At present time all available computers work on the base of an approximation curve as: (3)

$$\rho = A + B \cdot \frac{1}{f} + C \cdot \frac{1}{f^2} \quad \text{or}$$

$$\rho = A + B \cdot \tau + C \cdot \tau^2 \quad \text{where } \rho = \text{density}$$

f = frequency
 τ = periodic time
A,B,C = coefficients

Within the operating range the square curve very well covers the attitude of the densitometer. Surprisingly the square curve provides better results for lower densities.

The sensor of the densitometer type DIMB 104.2 is designed as a tuning fork with paddles at the end of each branch. These paddles provide a better ratio of $\frac{\Delta f}{f}$ vs. density variations by connecting a higher volume respectively a higher mass of the sample gas to the tuning fork sensor. (4)

The tuning fork is integrated into a closed loop with an amplifier that introduces energy only in a special way to overcome the frictions, but lets the sensor operate freely at its resonance frequency. So the resonance frequency depends on the sensor alone and the additional mass of the sample gas that is connected to it by the paddles.

Most applications of gas densitometers is in mass flow conversion. As one easily can see a misreading of the densitometer directly leads to an offset of all conversion results, as far as $\text{mass} = \text{volume}_{(\text{service})} * \text{density}_{(\text{service})}$.

The installation of a densitometer in a meter run has to be executed in a way that provides highest accuracy. (5)

For example a thermal insulation is required as far as gas changes its density on temperature changes. The feed pressure of the sample gas must not differ from that of the pressure tap. The sample flow rate has to be chosen under respect of the time delay after a change of the composition of the gas (Tests showed a time delay up to more than one hour depending on the installation of the sample pipework and caused by a low sample flow rate).

On standard applications the density range varies at 10 kg/m³ to 80 or 90 kg/m³, but the densities of liquid and solid particles is dramatically higher. This means all vibrating sensors for density measurement, independent on their design, must be protected as far as a contamination of the sensor will lead to an offset with higher density reading. (6)

All these problems can be solved by proper installation and maintenance of the instrument itself and the accessories. (7)

2. Influence of different gas types on the read out of the densitometer type DIMB

All densitometers based on a vibrating sensor depend on the reaction of the gas next to that sensor. As soon as the sensor starts its vibrations the gas column is forced to vibrate too at the frequency of the sensor system. Sound waves are emitted and travel along through the sample gas at the speed of sound.

Moments later these waves hit the surfaces of different parts inside the densitometer such as the guide tube or the bottom of the housing. The reflected waves now hit the sensor, in our case the tuning fork, and obviously strike back. It is a known fact, for example, that the distance between the tuning fork and the bottom of the housing is responsible for some misreading as soon as this distance is too short.

The tuning fork itself is located in the center of the guide tube and all radially emitted sound waves will return to that focus. Depending on the travel time the returning waves will hit the tuning fork sensor during a certain phase of its motion. If now the velocity of sound changes the sound waves will hit the sensor at a different phase angle and the introduced energy probably will have its influence on the attitude of the sensor and on its resonance frequency and on the read out result respectively.

Here now my private opinion: We do have to modify the densitometer and especially the parts around the sensor in a certain way to reduce reflections. Probably some sintered metal parts or other materials can absorb the energy of the original sound waves and reduce the reaction of reflected waves to the sensor.

At present time I am not able to provide test results already, they do not yet exist as far as this was one of the latest modifications of one of our densitometers.

The tuning fork itself is machined with sharp edges and while in motion the gas is forced to move forth and back. Next to the sharp edges of the sensor some shear will appear and the forces to overcome the friction depend on the viscosity of the fluid. (8)

If the shear zones could be reduced by a modified sensor the influence of different viscosities of the sample gas on the sensor also would be reduced.

We designed a tuning fork sensor where the paddles no longer are machined with such a long line of sharp edges but they are made of two tubes now. High shear zones do exist on the end of these tubes only, between and around the tubes there is a moderate shear only and no shear within the tubes.

The densitometers equipped with this type of sensor is named DIMB 200. It's base frequency differs to that of the standard type DIMB 104.2 (9)

If the DIMB 200 is calibrated by using methane and it is applied to natural gas the offset to be expected is within a range of approx. + 0.1 to zero percents.

On the other hand its' ratio of $\frac{\Delta f}{f}$ vs. density is lower compared

to the standard version. This is a reason why we recommend an application of the DIMB 200 for densities. (10)

The VoS-offset caused by other gases like nitrogen or ethylene is lower too by the same ratio but another attitude.

Other known effects with an influence on the readout is the attitude of the adhesion of the gas to the surface of the sensor. Another known effect is the capability of some gases to penetrate the metal of the sensor.

The best of all examples is given by the Ekofisk gas, where all our previous experiences were turned upside down. After the instruments were exposed to the gas, there a permanent drift occurred until a saturation was reached. The same thing happened in the opposite direction. When removed from Ekofisk gas and check with methane within a short time period there was a tremendous offset but after a few days the situation and results were back to normal. Similar offsets are known to the gas from Sibiria. (11)

Some attempts were done to reduce these effects. The best idea was to have the tuning fork teflon-coated or gold plated. The results in our and other labs and on field tests showed, that a coating of the tuning fork sensor can reduce the effects like mentioned above but other problems occur. As we found out the sensors react on different thickness of the coating and change their attitude on accuracy vs. density, but cannot prevent the so-called VoS-offset. The improvement of the readout was not as high as expected. So we can say a coating of a tuning fork sensor more or less will be useful for protection against aggressive gases. (4)

Bopp & Reuther does not only manufacture gas densito-meters, but also provides instruments for liquid density measurement. These instruments are named DIMF 1.2.

The sensor of these instruments are vibrating tuning forks again but their design is different. The sensors of the gas densitometers are submerged into the sample gas while the liquid sample of the DIMF 1.2 remains within the hollow tuning fork. This tuning fork is machined out of a single piece of metal with special bores inside. This design works very well for liquid density and so we put it on our gas density test rig and found some interesting results. As far as the sample gas remains within the sensor and the gas next to it is air and will not change, there is no or almost no shear of the sample gas. Sound emitted from the sensor is by air only under almost constant conditions. So after some development is done and some improvements are installed this instrument might be applied for gas measurement too. At present time it's a little too early to specify the instrument's limits and qualities, but we are still optimistic and will continue the tests. (8)

3. Correction of the VoS-offset by conventional means.

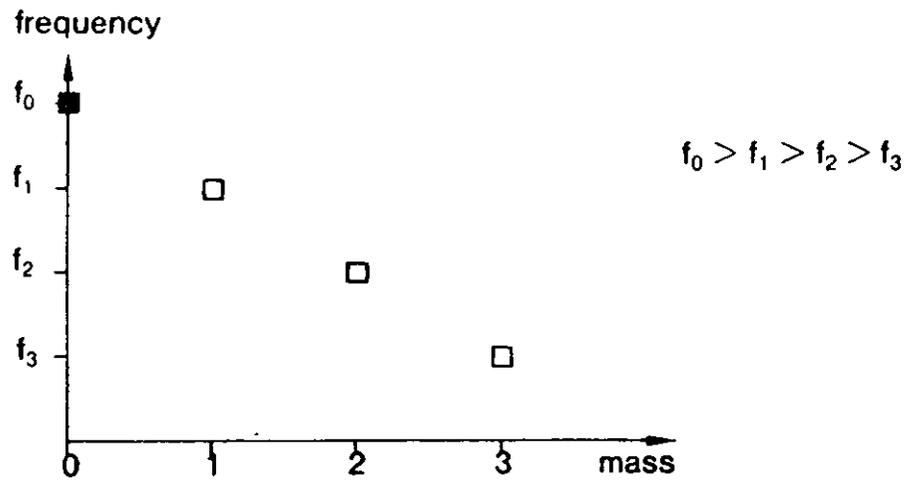
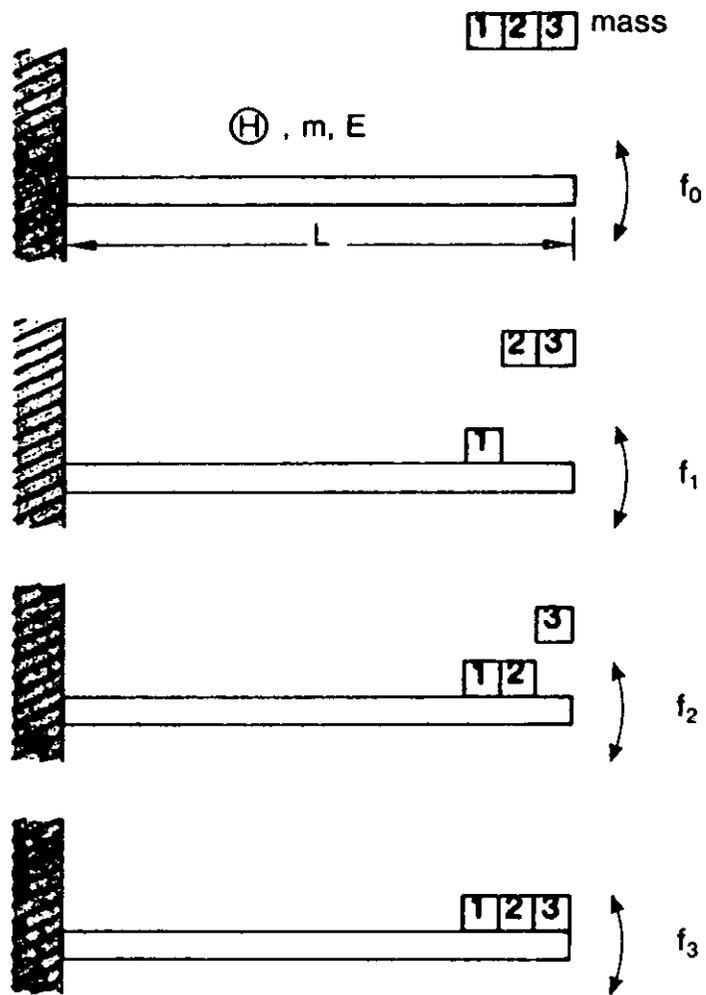
All attempts to overcome the VoS-offset by means of design and modification of the sensors or the instruments themselves have some encouraging results but the acceptance in the field is still low. Some of the first instruments delivered for field testing could not fulfill the expectations, had to be redesigned or improved in any way. As we think the DIMF 200 is ready now for field installations within the given limits. On the other hand there are systems of equations developed by the Ruhrgas Company and meanwhile approved by our authorities. These mathematical corrections gain the same accuracy for our standard instruments of + 0.1 percents and are based on the velocity of sound model. These equations require to know the velocity of sound of the sample gas where two ways exist to gain them.

The first way is to calculate the velocity of sound from some known or measured parameters like temperature, pressure, specific gravity and other information on the composition of the gas. The second way is to measure the velocity of sound as a live value by instrument.

Now we can look back the last few years where everyone was happy to gain an accuracy of 0.5 percent but now the requirements are to meet the 0.1 percent limit. So these requirements meet the lab test accuracy levels.

Quellennachweis

- J. Hennig - Ein Gerät zur Berücksichtigung der Dichte bei Gasmengenmessung
"Gas Wärme International" Bd. 22 Nr. 11 Nov. '73
- D. Ceelen - Dichte- und Normdichtemessung mit schwingenden mechanischen Strukturen
Lehrgang Nr. 8707/41.140 TA Esslingen '86
- M. Jaeschke,
H.-M. Hinze - Using densitometers in gas metering
Hydrocarbon Processing, June '87
- Internal reports of Bopp & Reuther GmbH



Titel:

Density Measurement by Vibrating Sensor

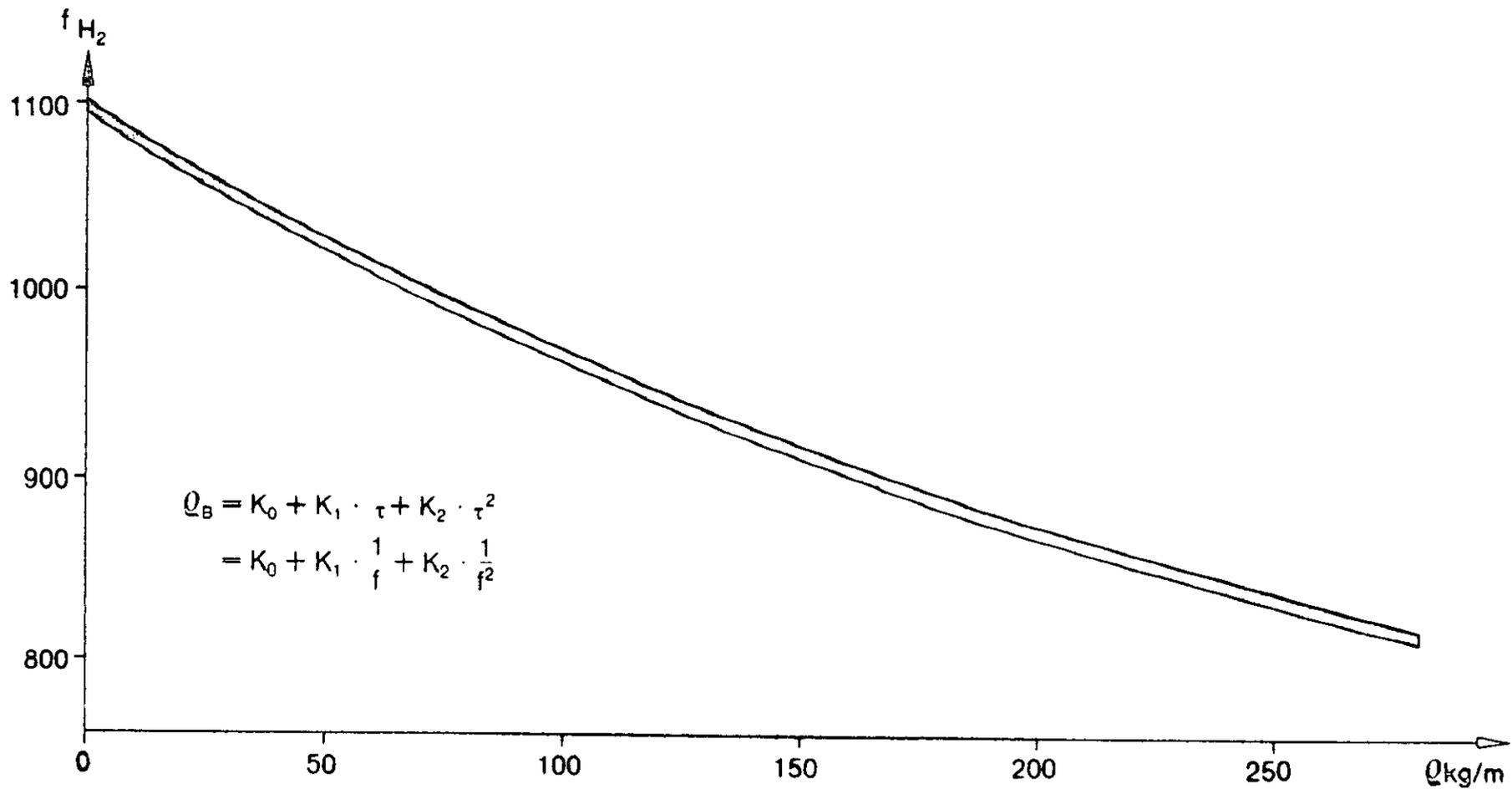
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$$Q_B = K_0 + K_1 \cdot \tau + K_2 \cdot \tau^2$$

$$= K_0 + K_1 \cdot \frac{1}{f} + K_2 \cdot \frac{1}{f^2}$$

Titel:

Frequency vs. Density of DIMB 104.2

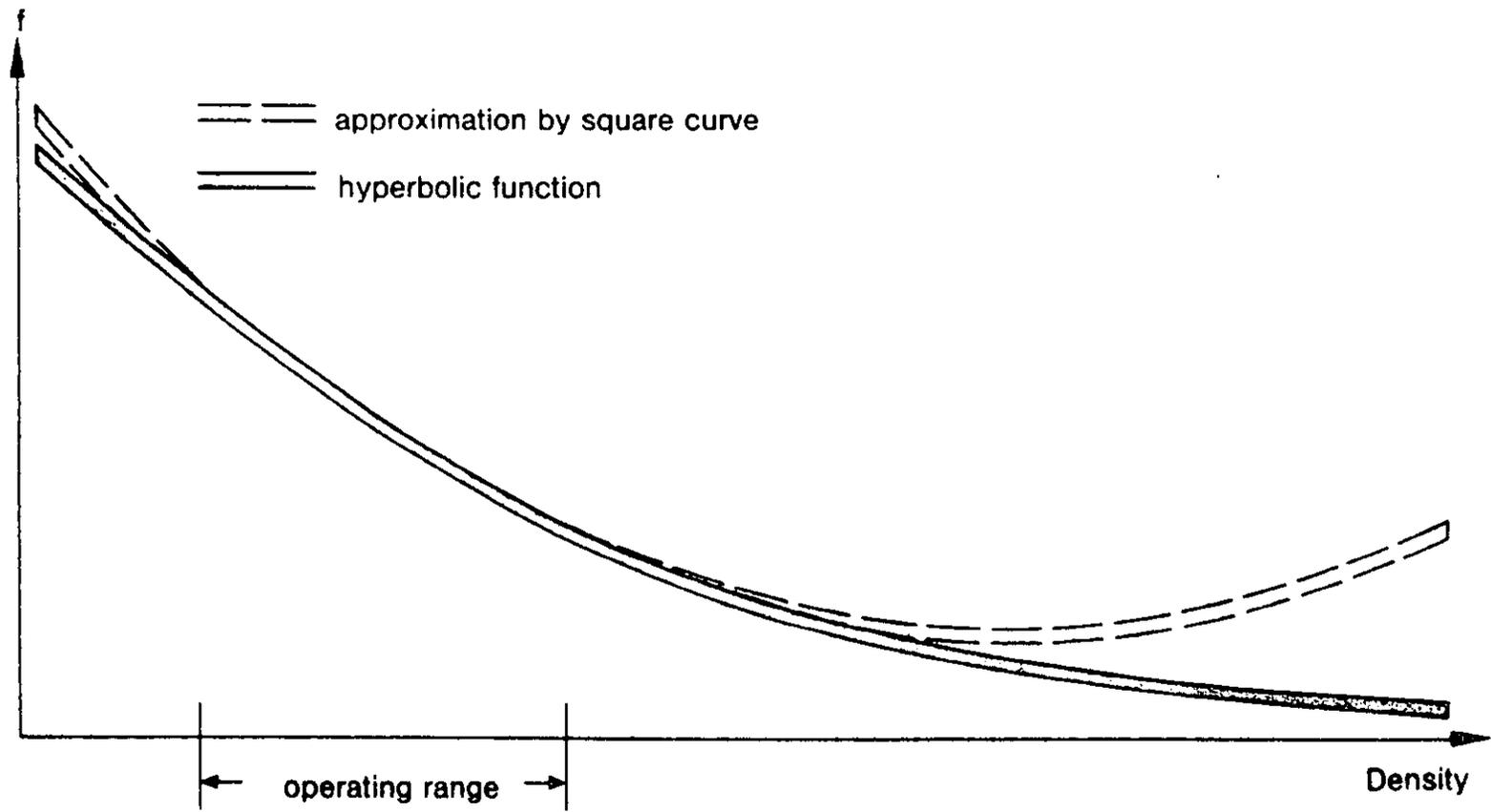
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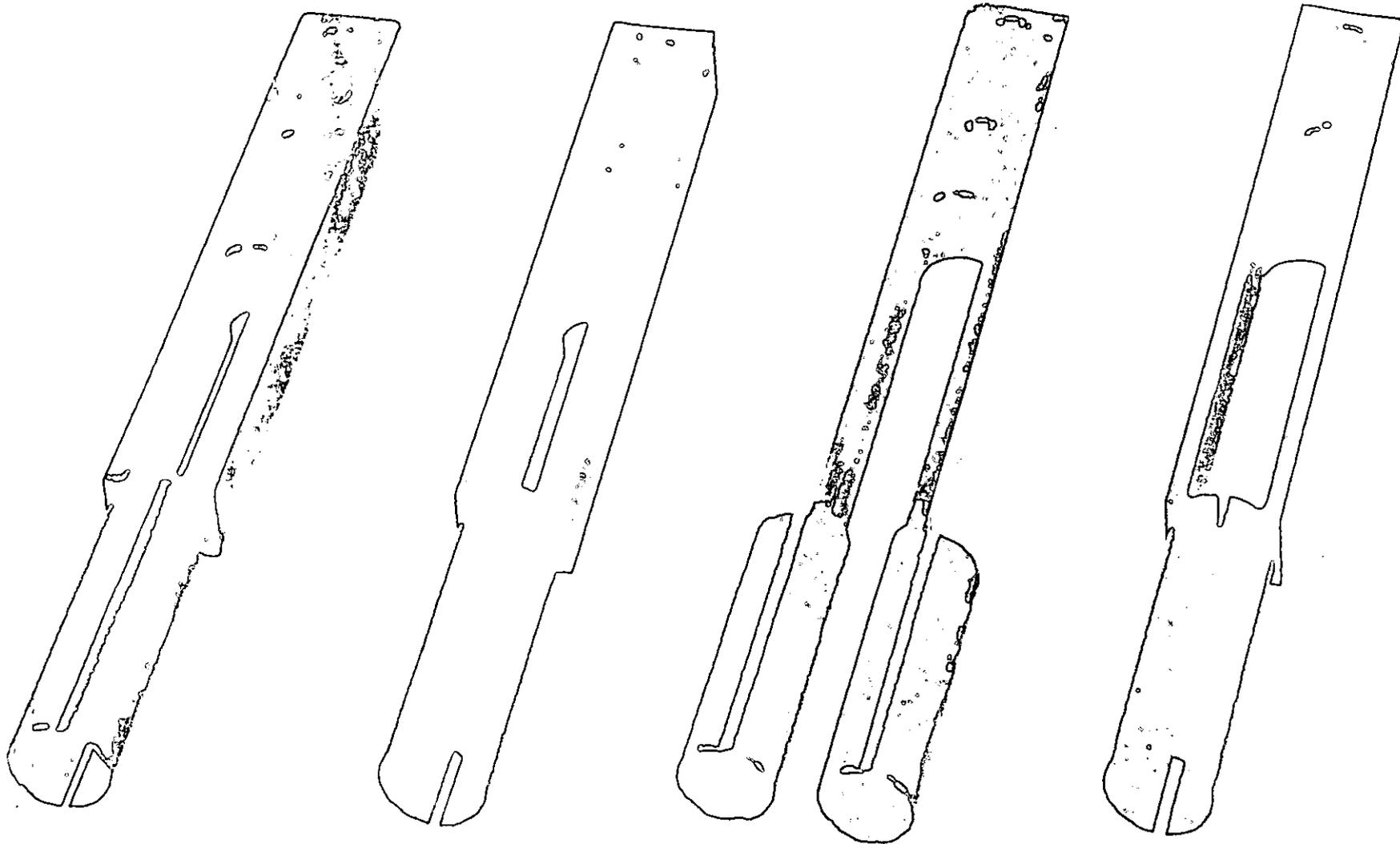


Titel: Attitude of resonance frequency of tuning fork compared to approximation by square curve

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Titel:

Different Designs of Tuning Fork Sensors

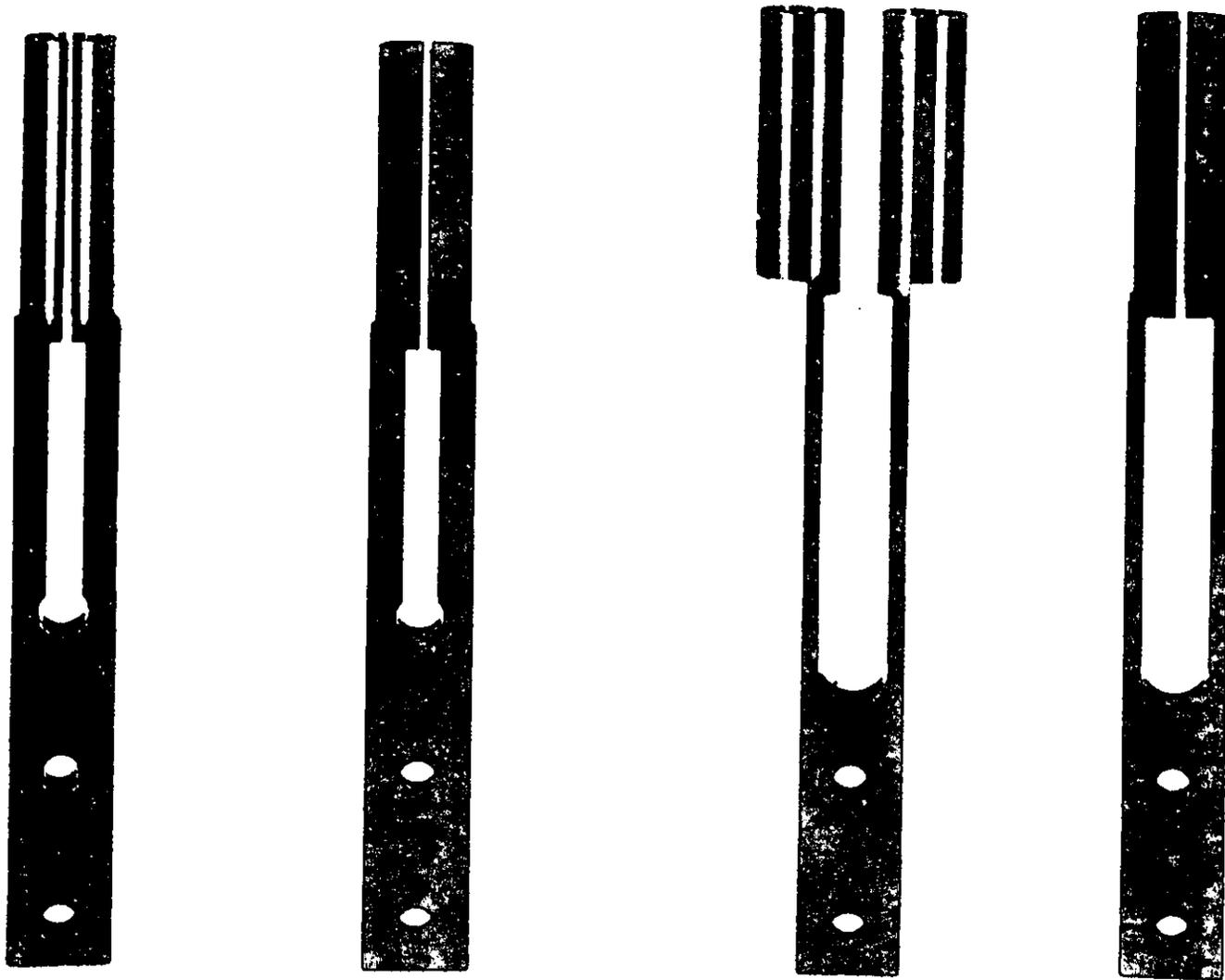
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Titel:

Different Designs of Tuning Fork Sensors

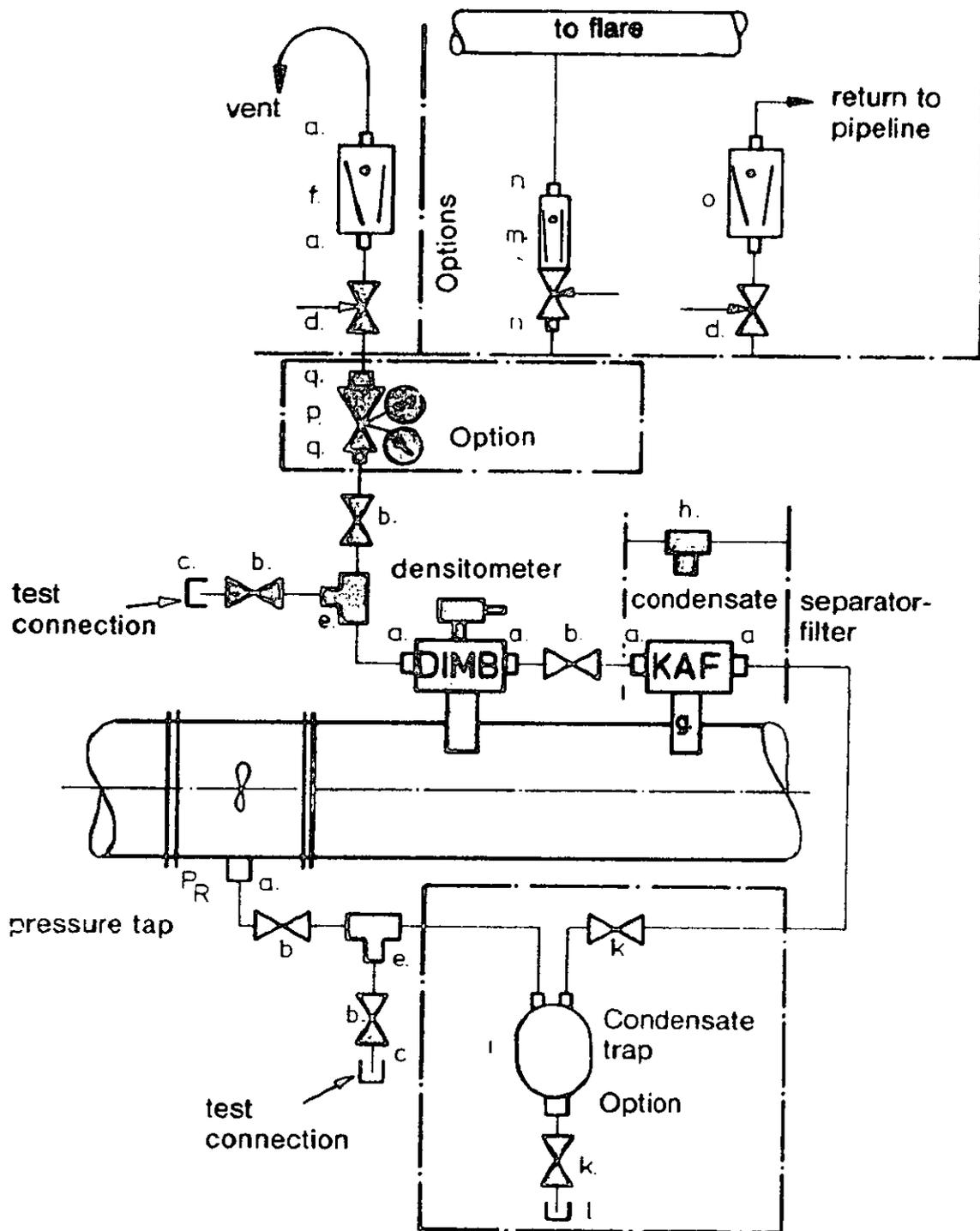
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Titel:

Accessories and piping for installation of gas densitometer

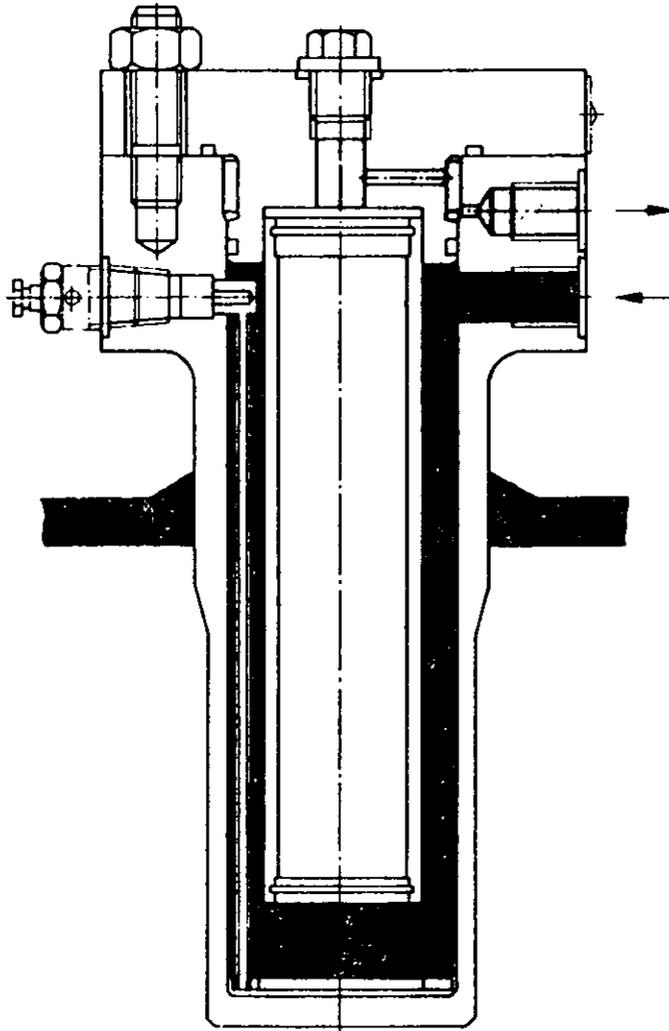
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Titel:

Condensate Separator - Filter Type KAF

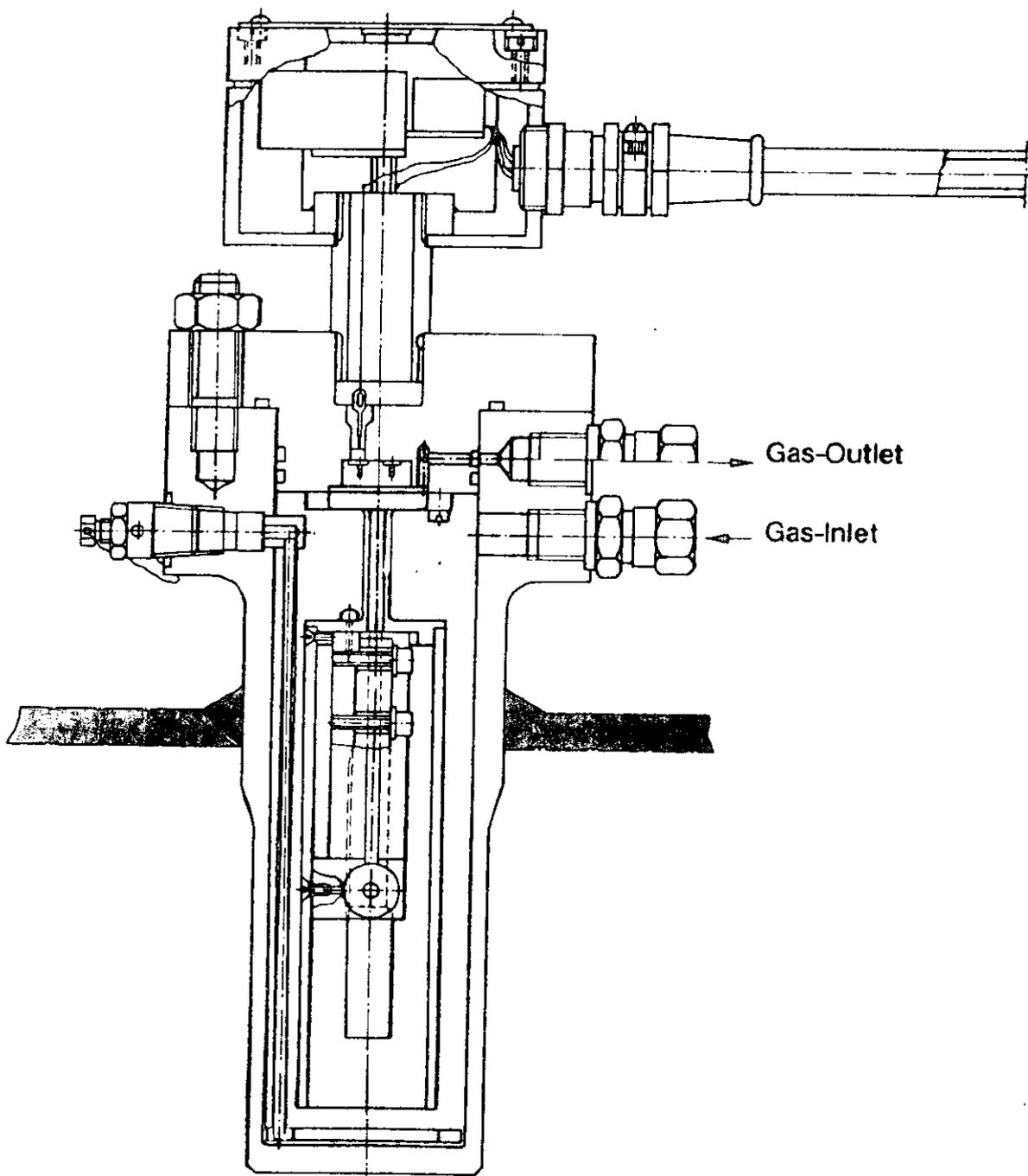
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Titel:

Gas Densitometer Type DIMB 104.2

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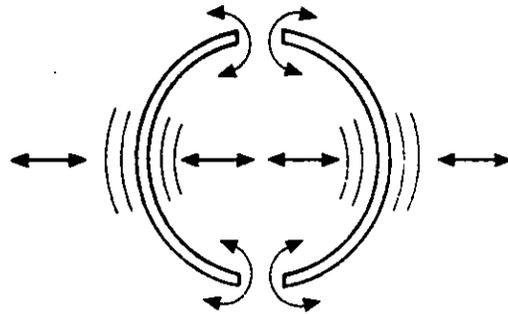
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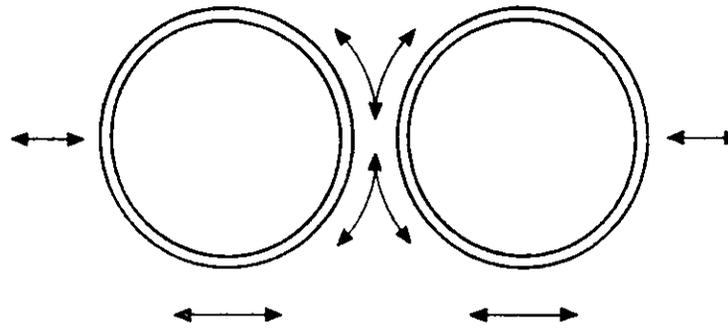
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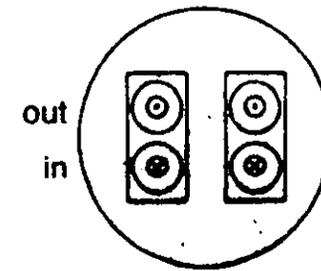
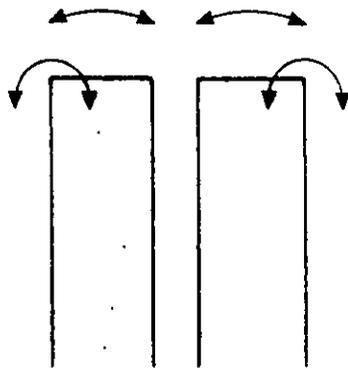
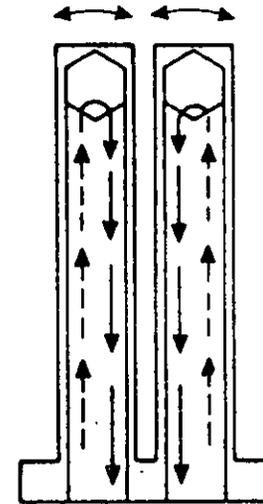
DIMB 104.2



DIMB 200



DIMF 1.2

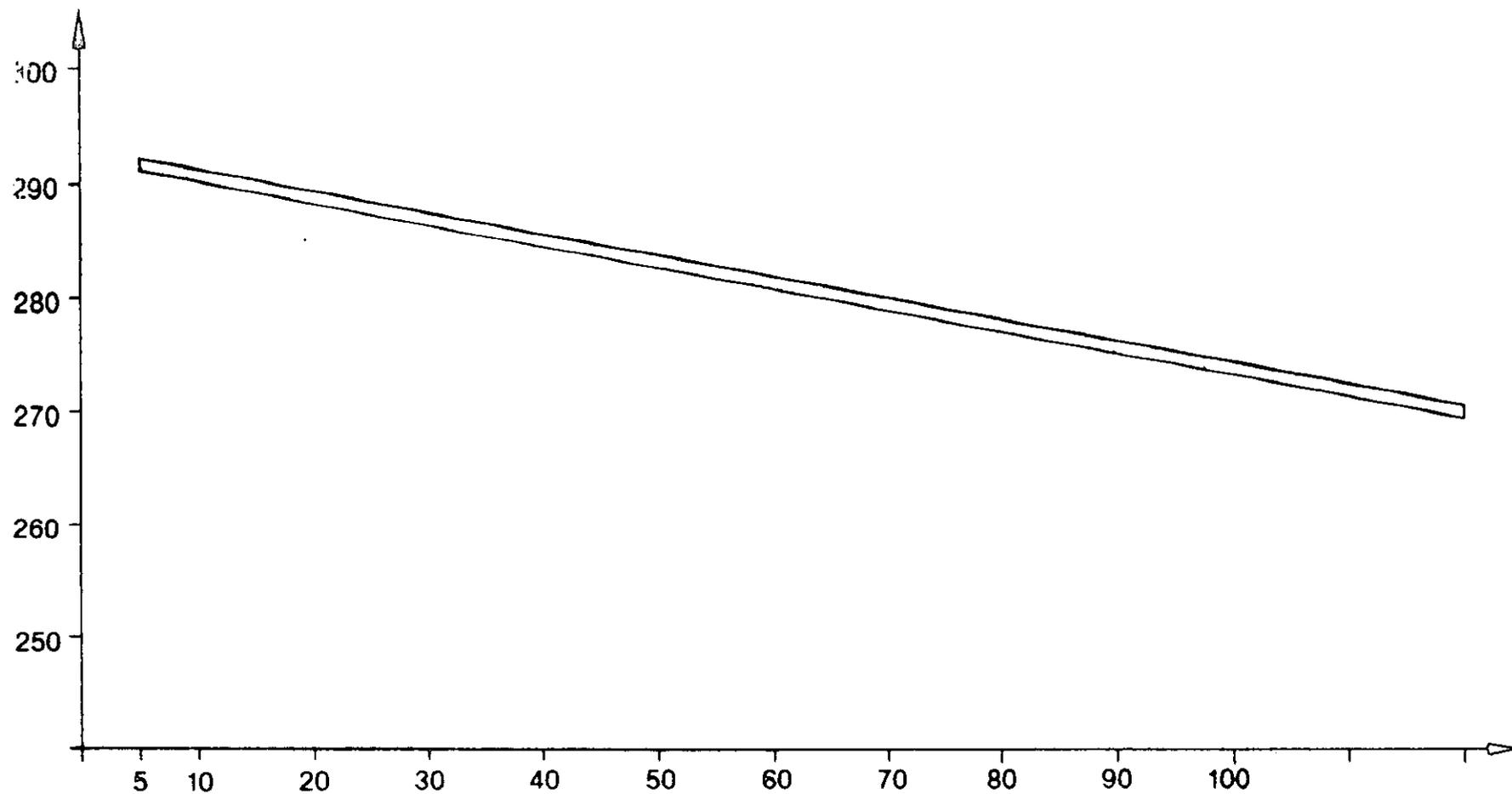


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Titel:

Frequency vs. Density of DIMB 200

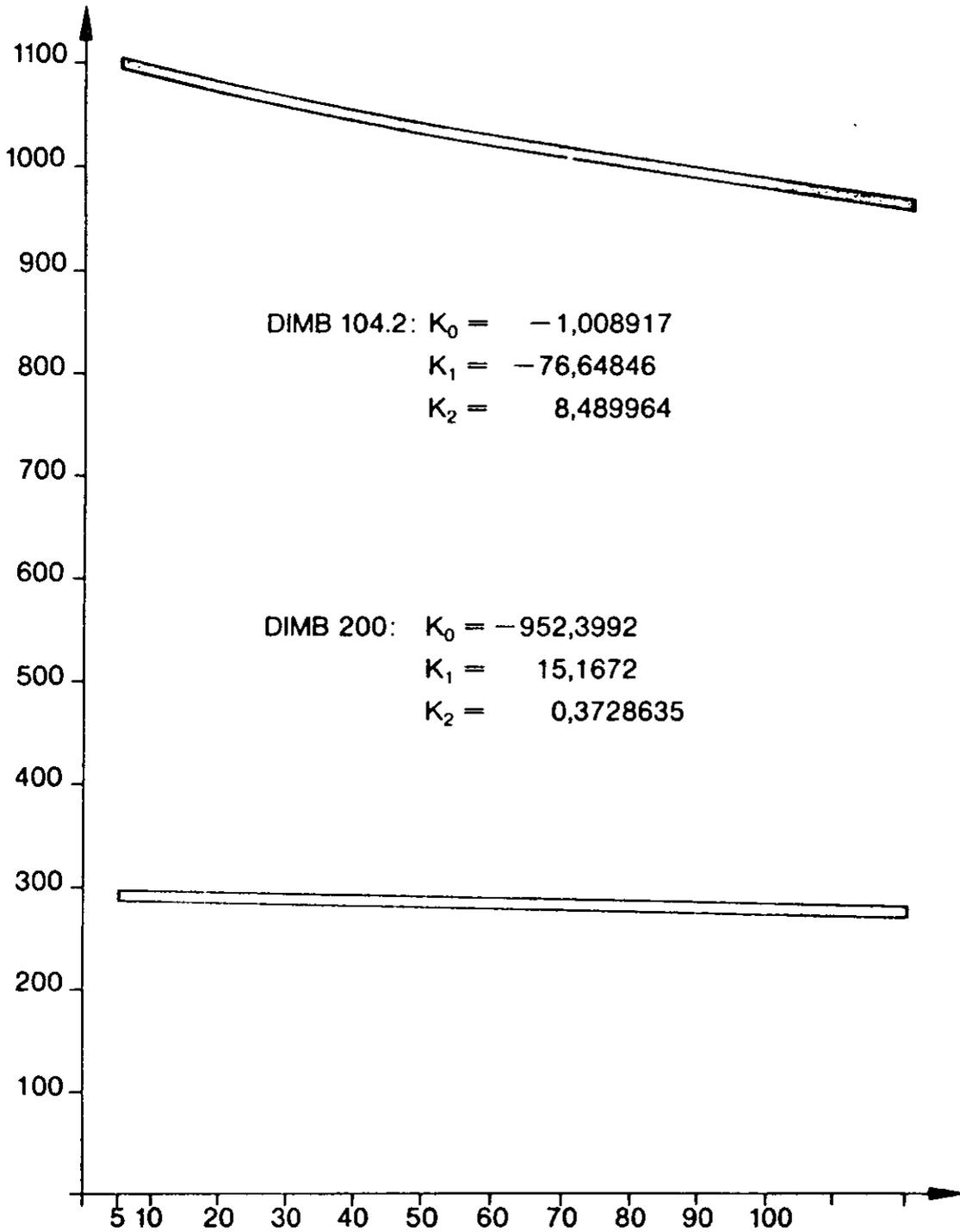
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Titel:

Frequency Relations of DIMB 104.2 and 200

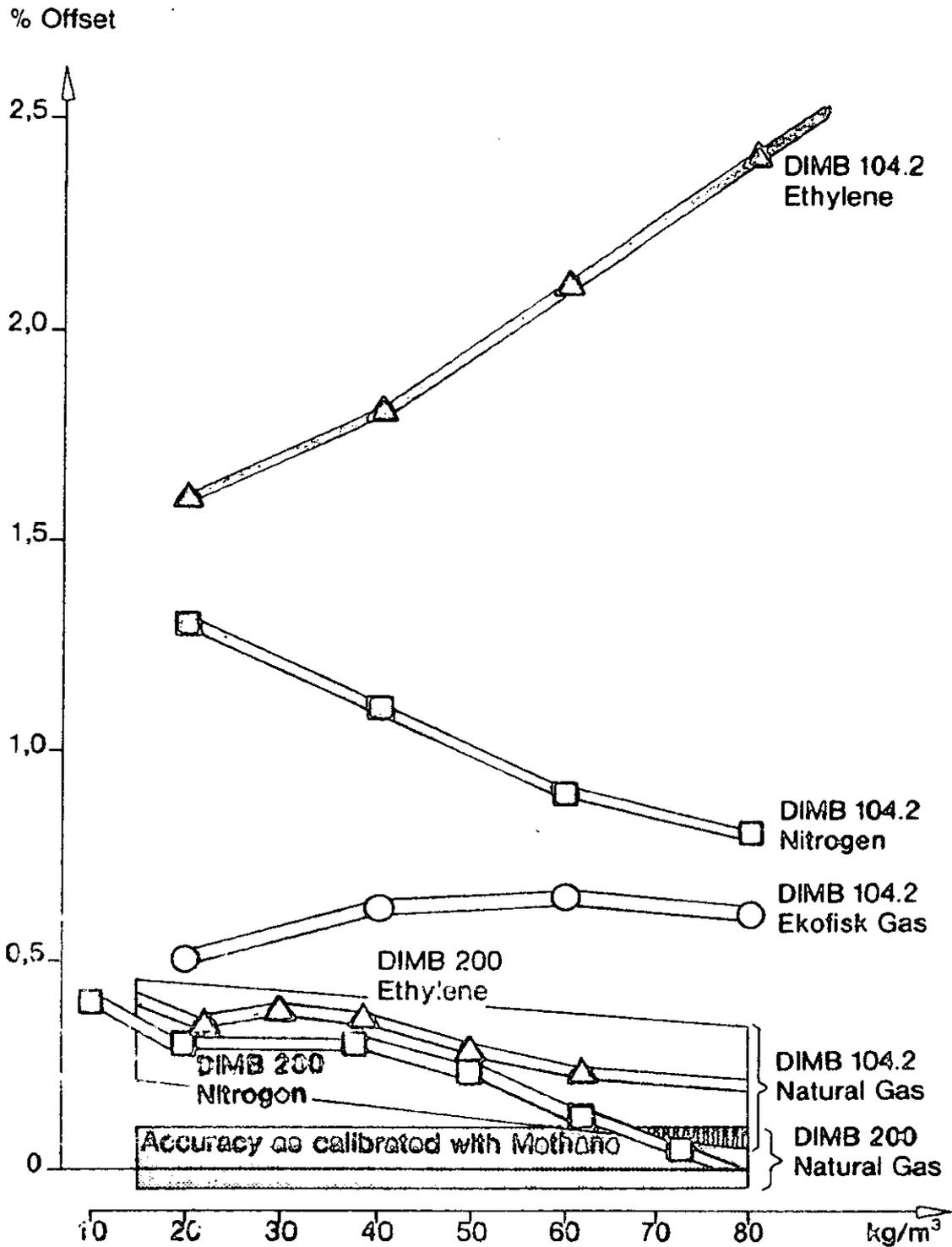
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Titel:

Velocity of Sound offset caused by different gases

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North Sea Flow Metering Workshop
Stavanger, 13 - 15 October 1987

Flare Gas Metering by Ultrasonic Measurement

by

Erling A. Hammer
Fluenta a/s, Bergen

2.3

INTRODUCTION

The ideal flaregas meter should be capable of measuring the complete range of velocities occurring in the flare pipe. It should be non-intrusive to avoid erosion or clogging of the sensor elements, thus reducing the necessity for frequent calibrations.

All of these objectives can be obtained by using an ultrasonic meter, but there are many technical difficulties which have to be solved to obtain a reliable and accurate instrument installed in a flaregas pipe.

A reliable flaregas meter has been developed by Chr. Michelsen Institute which is capable of measuring the flaregas flow in large diameter flare pipes with a velocity range of 0 m/sec. to 100 m/sec. It has a fast dynamic response to changes in flow conditions which can abruptly occur during shut-down condition.

This instrument has been developed over a period of 4 years and has been sponsored by Mobil Exploration Norway Inc., Statoil and Fluenta a/s. This instrument, the FGM-100 gas flowmeter is now produced by Fluenta a/s.

SYSTEM DESCRIPTION

The FGM-100 is a one-beam gas flowmeter designed to measure the complete range of flow velocities of potentially explosive gases flowing at low pressure in flare pipes.

Basic measurement principle

The FGM-100 is a transit time difference flowmeter. The transit time difference principle, also known as the time of flight principle, is the most common used measurement principle in industrial ultrasonic flowmeters and is based upon the fact that an ultrasonic pulse travelling between two transducers in the flow will have higher velocity downstream than upstream (Figure 1).

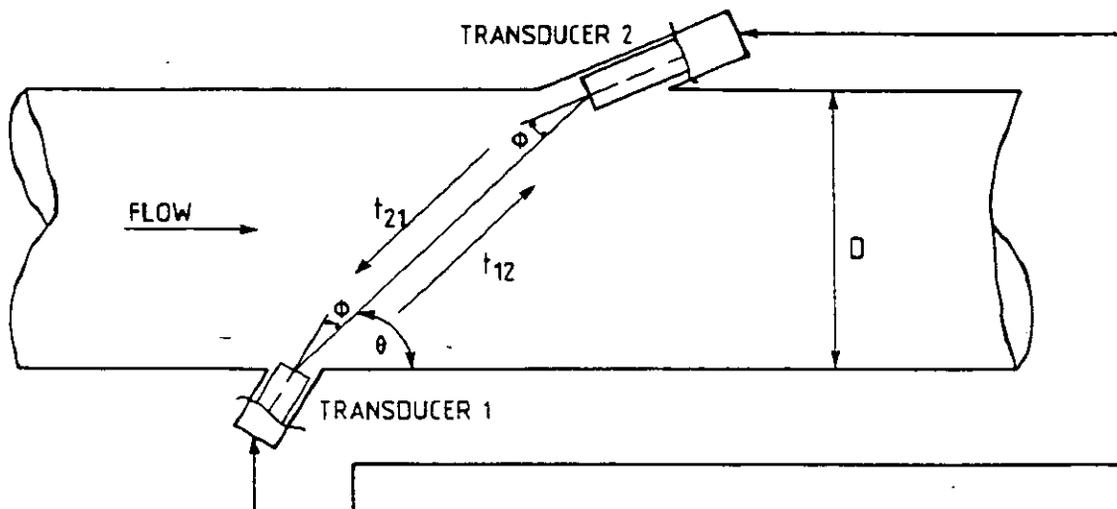


Figure 1. Transducer arrangement for FGM-100.

This measurement principle can therefore be used for flow measurement in homogeneous fluids and can measure the flowrate in both gases and liquids.

The difference in travelling times between the two transducers, upstream and downstream the moving medium, will be direct proportional to the flow velocity of the medium and can be expressed by the following formula:

$$\bar{v} = \frac{4D (t_{21} - t_{12})}{\sin 2\theta (t_{12} + t_{21})^2} = \frac{D (t_{21} - t_{12})}{t_{12} \cdot t_{21} \sin 2\theta}$$

where

\bar{v} = Mean flow velocity

D = Pipe diameter

θ = Angle of intertransducer centre line to axis of the pipe

t_{12} = Transit time from transducer 1 to transducer 2 (downstream)

t_{21} = Transit time from transducer 2 to transducer 1 (upstream).

As we can see from the formula, the mean flow velocity is independent of the sound velocity in the medium. This means that changes in sound velocity in the medium due to changes in temperature, gas composition, etc. do not influence the measurement results.

As shown in Figure 1 the two transducers are positioned facing each other at an angle Φ between the inter-transducer centre line and the transducer centre lines. The reason for this arrangement is that at high gas velocities the ultrasonic beam will be moved or 'blown away' from its initial transmitted direction along the direction of the flow, resulting in a curved path. The position of the transducers has been determined by means of theoretical investigations and verified during elaborated tests at the SINTEF wind tunnel. The transducer angle Φ has been determined in such a way that optimum signal condition has been obtained for the entire velocity range.

It can be shown that the formula given for the mean flow velocity also is valid even if the sound path, due to the 'blow away' effect, is unlinear. It is, however, important to be aware of that by positioning the transducers for compensation of the 'blow away' effect we have lost the possibility to use the meter for bi-directional measurements if only one pair of transducers is applied.

Transit time measurement techniques

The most common technique is the direct transit time measurement based on time measurement between the transmitted and received ultrasound signal. This technique can not be used in a flare gas meter because of the low resonance frequency of the transducers and the high level of transmission noise at high gas velocities.

It has therefore been necessary to use two different measurement techniques:

- a) For high and medium flow velocities:
 - A chirp signal technique with correlation detection to overcome high noise levels.
- b) For low velocities:
 - Continuous wave phase measurement technique in combination with the chirp technique.

The chirp measurement technique

To determine t_{12} and t_{21} the two transducers are used sequentially as transmitters and receivers. This technique utilizes a special excitation signal of a continuous varying frequency going from f_1 to f_2 during the duration of the pulse. This signal is called the chirp signal and has a constant amplitude.

At the receiver the transmitted signal contains the sum of the chirp signal and the noise generated signal which are totally uncorrelated to each other. This signal is now fed to the pulse compression block that contains a real time CCD-correlator which performs in principle a cross-correlation between the received signal and the incident chirp signal.

Figure 2 shows the autocorrelation function of a linear frequency modulated chirp with amplitude A which is a sinc-function with amplitude $A \cdot \sqrt{B\tau}$, where τ is the duration and B is the bandwidth ($f_2 - f_1$) of the chirp signal. The received chirp signal is now compressed and has a peak amplitude which is equal to the received signal multiplied by $\sqrt{B\tau}$. The FGM-100 uses a more elaborate function than the linear FM chirp, carefully selected with respect to the overall transmission path characteristics.

The maximum point of the compressed signal represents the time from the moment the chirp transmission started to the arrival of the entire chirp pulse. This time is detected by the chirp transit time detector block using a peak detector and a timer/counter circuit and is stored in the chirp transit time latch, to be read by the flow computer.

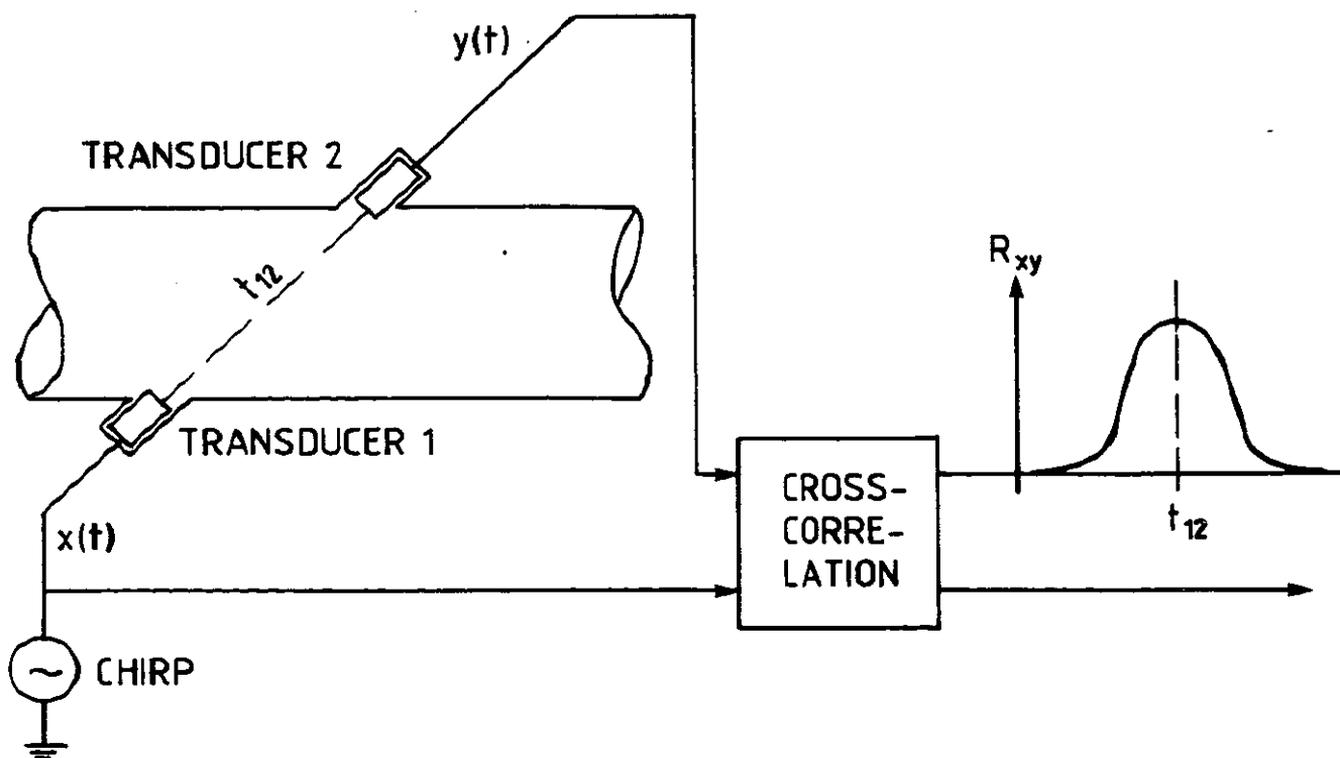


Figure 2. Principle of cross-correlation transit time measurement.

The improvement will increase with increasing duration and bandwidth of the chirp pulse and decreasing cut-off frequency of the generated noise. This implies that it is important to use transducers with high bandwidths. Due to the lack of high resonance peak in high bandwidth transducers the transmitted sound amplitude will be low compared with narrow band transducers. A compromise between those two characteristics must therefore be done.

The maximum point of the compressed received signal represents the time from the moment the chirp transmission started to the arrival of the entire chirp pulse. This maximum point is detected by a peak detector and a timer/counter and thus t_{12} and t_{21} can be measured.

Continuous wave (CW) phase measurement

For low velocities the CW-phase detection technique will represent a more accurate transit time measurement technique than the chirp technique. The CW-phase transit time measurement technique has therefore been chosen for velocities less than 10 m/s.

The inherent problem with CW-phase measurements is that for large variations in transit time the phase detector output will repeat itself at intervals equal to one CW-period. Hence, to ensure an unambiguous measurement it is necessary to know the number of whole CW-periods in the transit time. The chirp measurement is used to determine this number, while the CW-phase measurement gives the fraction. While this 'correction' to the CW-measurement could be done for each transit time, the FGM-100 only correct the transit time difference in this way.

A block diagram of the transit time measurement system is shown in Figure 3.

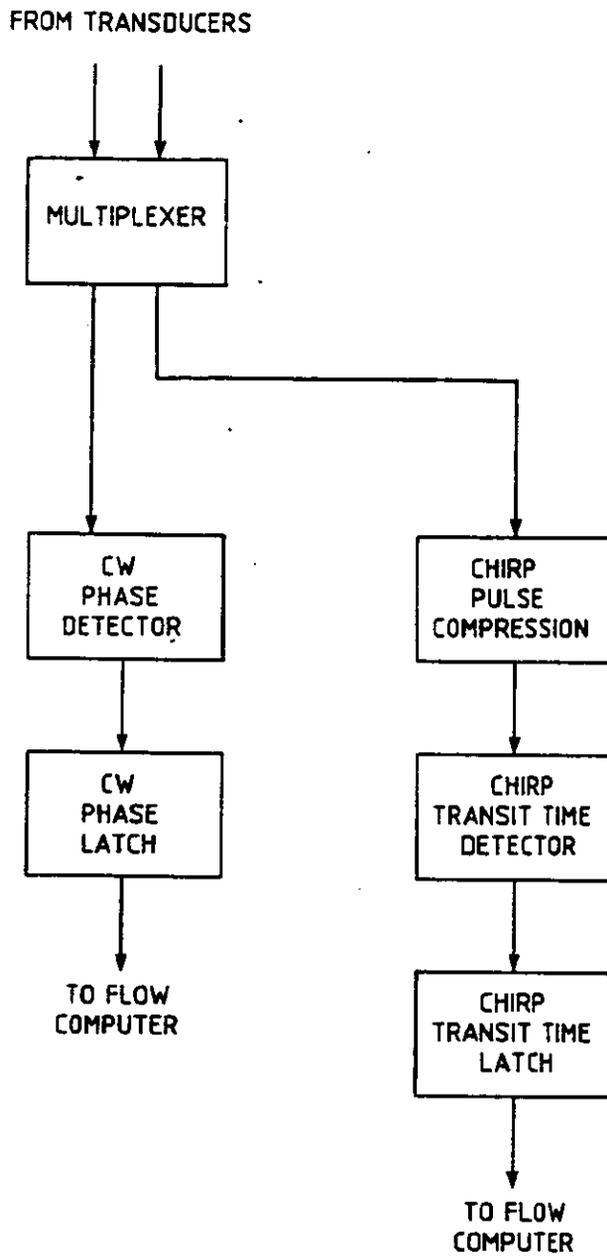


Figure 3. The transit time measurement system.

THE FLOW COMPUTER

The measured transit time is read into the Flow Computer from the CW-phase latch and the chirp transit time latch. In addition temperature, pressure and specific gravity (optional) are measured and read into the Flow Computer.

In the data filtering and evaluation block the transit time data are evaluated and 'noise measurements' are filtered out.

From the filtered data, the gas flow velocity is calculated from the formula given above. The velocity is then compensated for pressure and flow-profile variations along the section of the pipe. Then, standardized volume flow is calculated from the evaluated velocity using the measured temperature and pressure values obtained from the sensors placed on the pipe.

Mass flow is calculated from the standardized volume flow and measured or calculated specific gravity.

Totalized volume flow and mass are also calculated.

General layout of the complete signal processing system is shown in Figure 4.

THE ULTRASONIC TRANSDUCERS

Measuring flaregas flow we get into the difficulty that the gas pressure is low and hence, the acoustic impedance of the gas is low.

Due to safety reason the ultrasonic transducer should be encapsulated in steel or other strong resilient materials which will have a high acoustic impedance. The large difference in acoustic impedances will result in a poor acoustic coupling between the transducer and the gas at low pressure.

Ordinary piston mode transducers can therefore not be used.

CMI has, however, succeeded in developing a new type of transducers which has a much better acoustic coupling to the gas than the piston mode types, even at low gas pressure. These transducers are made out of titanium, operate in flexure mode and are tuned to transmit and receive in the vicinity of the frequency of 80 kHz.

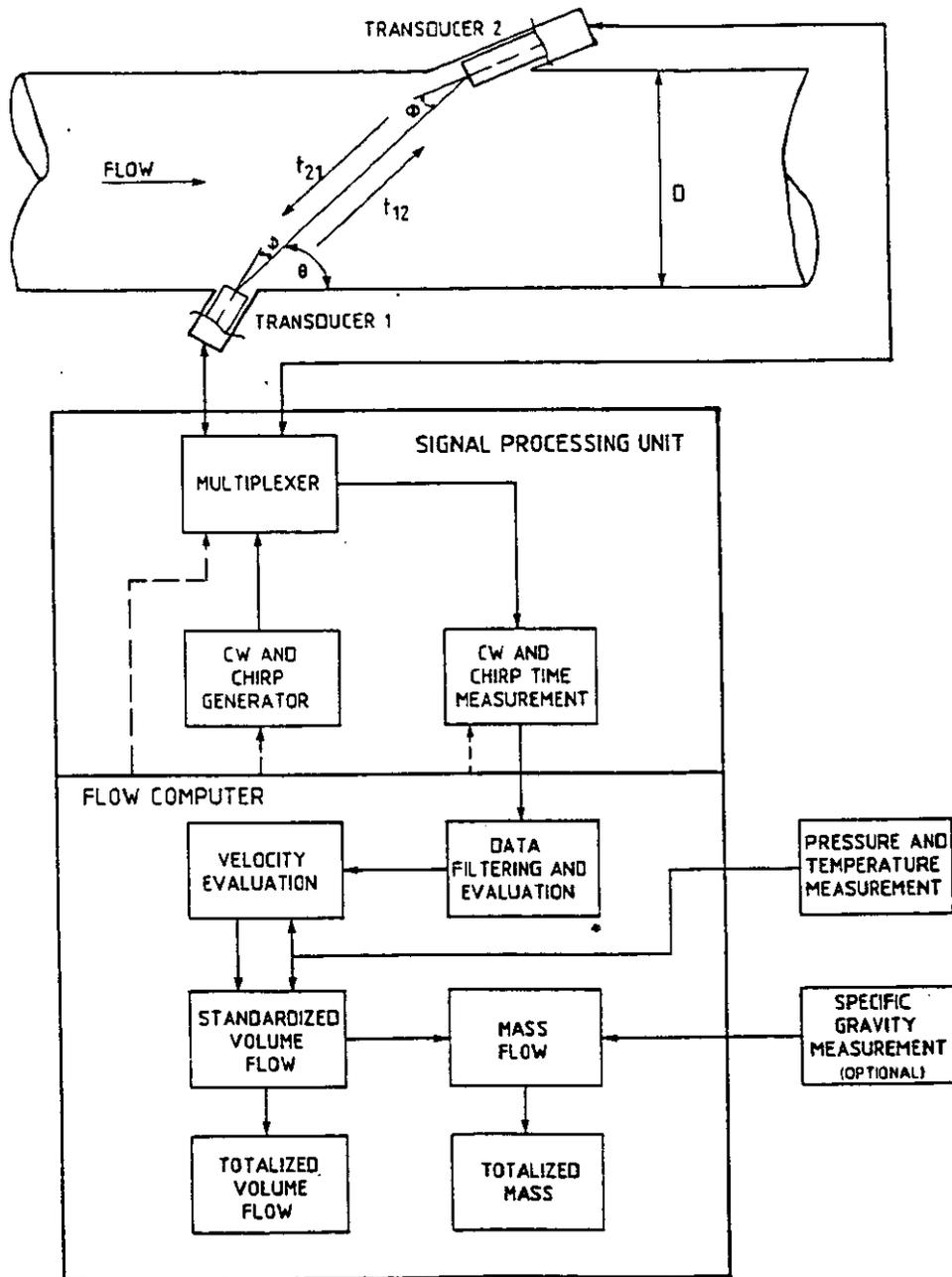


Figure 4. General layout of the signal processing system in FGM-100.

Due to safety considerations, the mandatory certification required for electronic and electrical systems has been obtained for these transducers from BASEEFA of the Health and Safety Executive of the United Kingdom.

In addition, the system placed in the flowpipe has a BASEEFA system certificate.

Elaborated tests and investigations of the transducer housing and type of damping materials have resulted in a transducer with sufficient band-width to be used in an efficient chirp system.

THE SIGNAL TRANSMISSION SYSTEM

One unique feature in the FGM-100 flowmeter is the usage of optical fibres for transmission of signals between the ultrasonic transducers and the signal processing unit. The usage of optical fibres improves the resistance of the system to EMI-noise considerably.

The type of fibre used in the FGM-100 Ultrasonic Gas Flowmeter is shown in Figure 5.

The sheet containing the optical fibre is flame resistant and has been used in fibres used on offshore installations. The non-metallic 4-fibre cable of NEK Kabel A/S is specially designed for data communication and can withstand temperatures upto 125°C.

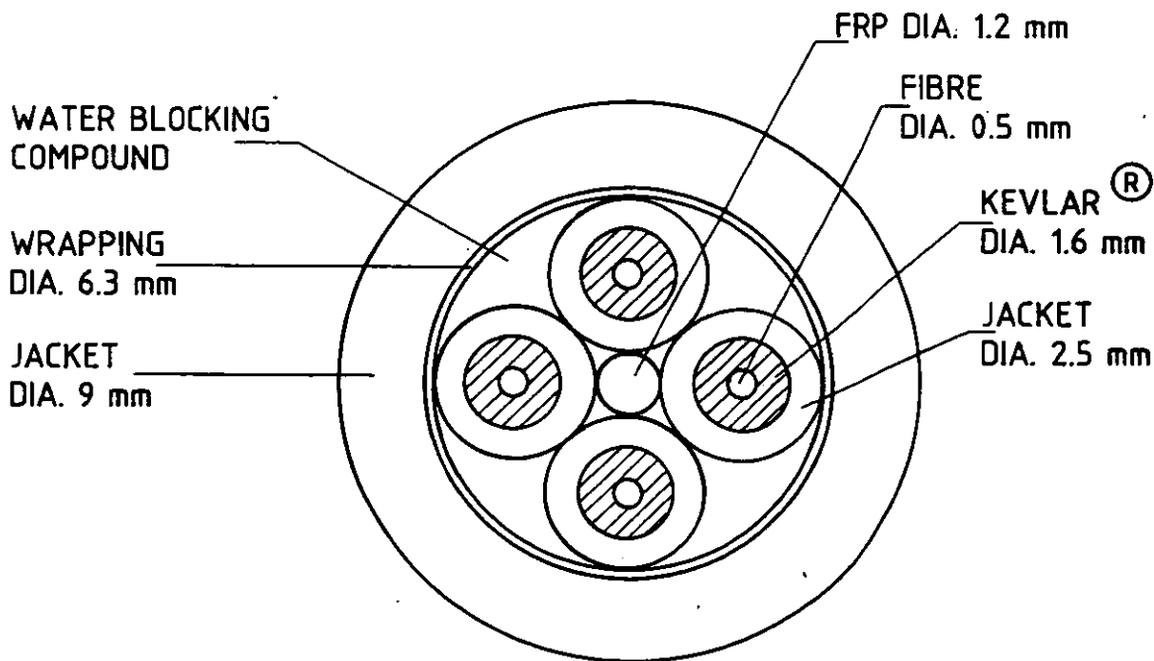


Figure 5. Optical fibre signal transmission cable.

SYSTEM LAYOUT

The system layout is shown with the principal units in Figure 6. The principal units are the following:

- CMI-Ultrasonic transducers
- Certified power supplies
- Two pairs of optical cables
- Signal processing unit
- Flow Computer
- Sensors for monitoring certain state variables of the gas
- Recording unit
- Key Board with alpha-numerical display.

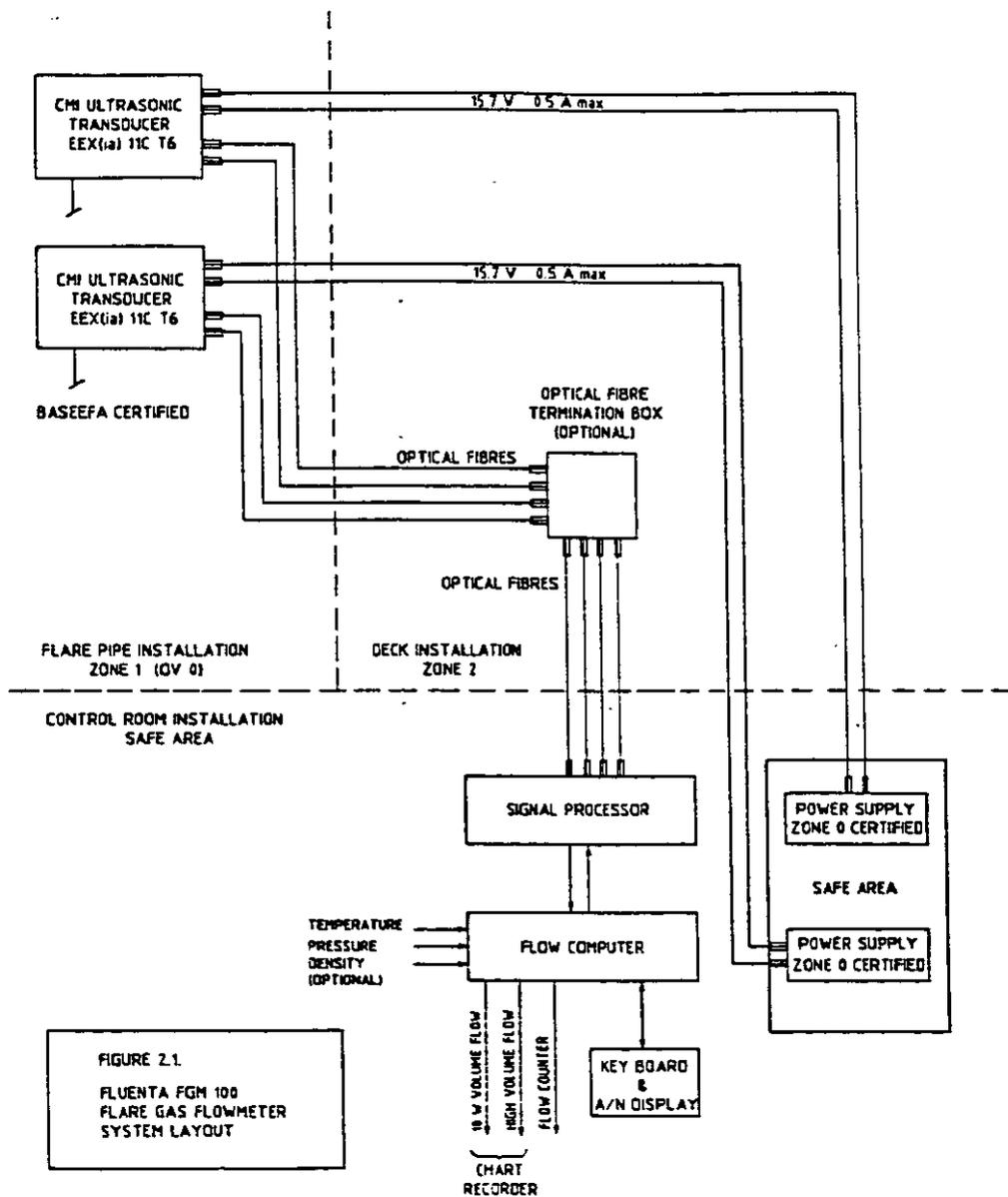


FIGURE 2.1
FLUENTA FGM 100
FLARE GAS FLOWMETER
SYSTEM LAYOUT

Figure 6. The system layout of FGM-100 Flare Gas Flowmeter.

As can be seen in Figure 6, these units are placed in various safety zones during actual installation. The zones specified in Figure 6 are:

- Zone associated with the transducers in the pipe in which the gas to be monitored is flowing. This is usually Zone 1 on offshore installations.
- Zone associated with the installations direct on the deck serving the transducers. This is usually Zone 2 on offshore installations.
- Control room, in which the signal processing unit and the flow computer are placed with the peripheral units for communication to the personnel in the control room. This is a 'safe area' according to the zonal classifications. The optical fibres carrying the signals associated with the ultrasonic interrogation of the flow are terminated in the terminal box with fibres of fixed length connected to the ultrasonic transducers. The rest of the fibres going to the control room can be of varying length, depending on the application.

TRANSDUCER MOUNTING

The transducers can be mounted on the flare pipe using specially designed rigs for accurate transducer orientation. The transducer mounting tubes are fitted with ball valves arranged in such a way that the transducers can be removed from the flare pipe without shut down of the flare. This is shown in Figure 7.

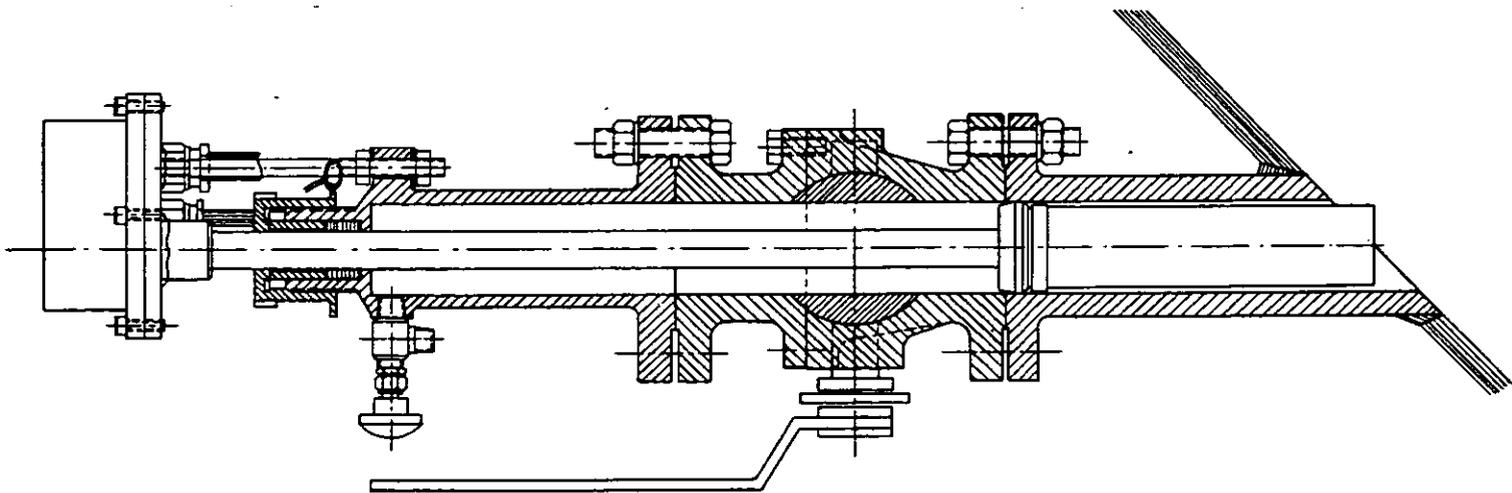


Figure 7. Transducer carrier unit.

SYSTEM PERFORMANCE

The FGM-100 Ultrasonic Gas Flowmeter has been designed to deal with difficult flare gas flow-metering problems; high turn-down ratio, and rapidly varying flow-rates and strict safety standards for devices utilized in explosive or potentially explosive environments.

As a result of extensive R&D, the meter has the Veritas certificate for mechanical stability for usage on Statfjord B platform, and BASEEFA certificates for intrinsic safety of the ultrasonic transducers and for the whole system. The model has undergone extensive tests in wind tunnel facilities in Norway. The BASEEFA certificates are for safety class EEXiaIICT6 and have the following numbers: EX 86B2411 and EX 872089.

The special transducer design and unique signal trains, containing unusual signal forms not found in other ultrasonic flowmeters, make it possible for the model FGM-100 to monitor flow velocities of gases at high turn-down ratios.

In addition, the frequent interrogation of the flow and advanced real time filtering of data make the meter an accurate device which combines robustness and easy installation with intrinsic safety.

The flowmeter has been tested between 0.05 m/s and 100 m/s in pipes with diameter of 36" (about 1 m). The overall uncertainty at 95% confidence level was found, from the wind tunnel tests, to be around 5% of measured value at fully developed turbulent conditions in the range 0.3-70 m/s. The restricted velocity range of 0.3-70 m/s for the confidence level was determined by the windtunnel and reference flowmeters and not by the FGM-100.

The uncertainty was found to be around 3% of measured value for velocities around 20 m/s. The resolution is 0.01 m/s in 36" diameter pipes. The repeatability of the meter was found to be 1% of volume flow for velocities from 0.3 m/s - 70 m/s in 36" diameter pipes.

ACKNOWLEDGEMENT

The author of this paper would like to express his sincere thanks to the project group at Chr. Michelsen Institute who has performed the development of this instrument and to Statoil and Mobil who have had the encouragement and patient to sponsor the introduction of a new measurement technique for offshore use.

NORSKE SIVILINGENIØRERS FORENING
NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

NORTH SEA FLOWMETERING WORKSHOP
STAVANGER
13-15 OCTOBER 1987

EXPERIENCE WITH A SMART "DP" TRANSMITTER

2.4

LECTURER: TROND HJORTELAND
STATOIL
DRIFTSDIVISJON STAVANGER

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EXPERIENCE WITH A ST3000 SMART TRANSMITTER

1. INTRODUCTION

1.1 Presentation content

This presentation will include test results and experience in application of Honeywell ST3000 smart pressure transmitters. Both differential pressure and static pressure transmitters have been utilized on the Statfjord field since early 85.

The transmitters are installed in fiscal gas metering stations for measurement of differential pressure and line pressure in orifice meter runs.

The gas is fed to the Statpipe system on Norwegian sector and to NLGP/FLAGS on the UK sector.

The main objective with the presentation is to summarize experience from the following phases:

- a) Selection of equipment.
- b) Installation and commissioning.
- c) Operation.

The comments are made based on experience from personnel involved with maintenance work.

The main references for the overall quality of the transmitter will be based on the following:

- a) High accuracy
- b) User friendly
- c) Availability
- d) Reliability
- e) Stability in calibration

1.2 Summary

1.2.1 Description

The transmitter features a new concept in the measurement of process parameters. Communication via its 4-20 mA loop makes this transmitter unique and provides the capabilities of remote transmitter adjustments and diagnostics. This is accomplished via a hand held communicator and enables the operator to perform changes in transmitter configuration from the control room.

The sensor is a piezo resistive element and microprocessor based electronics provide enhanced accuracy by compensation of output signal (temperature and static pressure compensation for differential pressure measurement).

1.2.2 Experience

Problems occurred during the selection and commissioning phase. During the onshore testing phase, prior to purchase, leakage and accuracy problems were revealed: leakage in process head during ambient temperature test and problems with compliance with manufacturers specification during measurement accuracy testing.

However, these problems were resolved and we will concentrate on experience from the operational phase.

The main requirement we emphasized during selection phase was the transmitter's accuracy. In general the ST3000 have been a reliable, user friendly and in our opinion probably one of the best instruments available on the market today. However, other manufacturers offer transmitters based on the same smart concept with similar high quality specification. We have experience with ST3000 only and this presentation will not include comparison with other manufacturers.

The calibration stability of the ST3000 have proven to be very good and we have been able to reduce maintenance cost since calibration intervals have been extended.

2. DESCRIPTION OF INSTRUMENT

Ref. Fig. 1 and specification sheets.

2.1 Introduction

The intention is not to fully describe all the details of the transmitter's features and functions. Please refer to the technical manual for details.

This presentation will concentrate on the transmitters main new features.

The ST3000 microprocessor based transmitter performs measurement of differential, gauge or absolute process pressure. The piezo resistive sensor combined with the microprocessor based electronics and digital to analog converter provides an analog 4-20 mA output signal proportional to the measured signal.

The ST3000 was designed as a direct replacement for conventional analog transmitters. It uses the existing 4-20 mA lines for power, signal transmission and communication.

One of the new main features include remote communication with the transmitter through the Smart Field Communicator (SFC). This unit provides the capabilities of remote adjustments and diagnostics.

The ST3000 family includes instruments for a wide range of application areas with measurement of the following process parameters:

- a) Absolute pressure
- b) Gauge pressure
- c) Differential pressure

This presentation will concentrate on the measurement of differential pressure.

2.2 Sensing element

The ST3000 transmitter utilize a piezo resistive sensor with no mechanical parts.

The piezo resistive strain gauge sensor is an electric wheatstone bridge circuit ion-implanted onto a silicon chip. The sensor is sealed and isolated from the process by metal diaphragms and silicone fluid.

This integrated sensor provides three analog signals; process pressure, sensor temperature and static pressure.

These three analog signals are converted to digital signals for input to the microprocessor. The processor utilizes factory calibration data stored in PROM and calculates appropriate output values, compensating for the existing temperature and static pressure conditions.

This value is then converted back to an analog signal, resulting in an 4-20 mA output signal.

2.3 Electronics

The housing contains separate compartments for the electronics module and an integral junction box separated from the electronics.

The electronics module is replaceable and interchangeable with any other ST3000 model.

2.4 Communication with the transmitter (SFC)

See Fig. 1.

Communication with the transmitter is performed with a handheld communicator hooked up to the 4-20 mA instrument loop.

This unit may be utilized for the following operations:

- a) Configuration
- b) Troubleshooting, diagnostics
- c) Calibration
- d) Display data
- e) Monitoring of measurement results

2.5 Summary of the transmitter's main features

a) Improved accuracy

Live compensation measurement in conjunction with calibration data from factory stored in memory provides improved accuracy and stability. See specification sheet.

Important aspects giving effect for overall measurement uncertainty:

- Static pressure effect on differential pressure measurement.
- Ambient temperature effect.
- Hysteresis.

b) High turndown ratio

Large range of span adjustments gives a maximum of 400:1 in turndown ratio.

- This feature allows a lower number of various transmitter models on stock to cover the ranges required.
- Provision of range changing flexibility.

c) Remote adjustability

Communication with the transmitter is performed from control room.

This feature allows the operators to perform changes in functions and reranging without having to enter the process location and remove transmitter.

d) Diagnostics and start up

The concept of remote communication is timesaving in diagnostics work.

e) Commissioning

The transmitter may be utilized as a current generator and thereby commissioning on total loop work may be completed in a shorter time.

In general the remote communication concept provides great improvement during commissioning and startup work where configuration changes are required to "tune" the process.

In our application ranges are fixed and thereby the possibility of reranging does not apply for our present installation.

3. CALIBRATION. METHODS AND PROCEDURES

3.1 Requirement

Fiscal measurement of petroleum products has to comply with regulations from authorities. Norwegian Petroleum Directorate has issued regulations for gas:

Regulation for fiscal measurement of gas produced in internal waters, in Norwegian territorial waters and in the part of the Norwegian Continental Shelf which is subject to Norwegian sovereignty.

In these regulations it is stated (§63) that calibration intervals for transducers are every month. Based on experience with equipment, dispensation from regulations may be granted.

Additionally, industrial practice within custody transfer set requirements for gas sales.

The calibration method and procedure should be approved (recognized) by authorities, partners and buyers.

3.2. Differential pressure and static pressure

3.2.1 Introduction

The differential pressure (DP) is a vital parameter in an orifice measurement system. We have therefore emphasized the importance of the quality of the DP-measurement in order to keep the overall station measurement uncertainty as low as possible.

The static pressure measurement is utilized in secondary correction to the gas flow measurement. However, it is considered to be an important parameter and we have therefore aimed for high quality instrumentation during selection phase of test equipment and transmitter.

The following description gives an outlined version of the detailed calibration procedures and test equipment.

This procedure is included in the

Gas Metering Calibration and Maintenance Manual for The Statfjord Field

Test and calibration work is performed both offshore and onshore (DP). For static pressure we perform calibration offshore only.

3.2.2 Testing and calibration

Requirement

All fiscal measurement will require test equipment with very high accuracy and certified traceability to national standards.

Requirement for onshore calibration:

0-100 mbar: 0.275%
0-500 mbar: 0.15%

Traceability

For differential pressure measurements we have certified traceability to the French National Standard via LNE (Laboratoire National d'Essai)

For voltage measurement (measurement for transmitter output across a precision resistor) we have certified traceability to the British National Standard via NPL (National Physical Laboratories).

Equipment. Differential Pressure

Ref. fig. no. 2.

Onshore

Des Granges et Huot pressure standard 5303
Des Granges et Huot divider 1500

This system features the capability of applying differential pressure to the transmitters at a given static pressure.

Voltage & Resistor

Voltage measurement: Solartron 7081
Precision resistor: Cropico RS3

The transmitter (4-20 mA) output is measured across a 250 precision resistor.

Offshore

Pressure

AMETEK pneumatic DWT.

Voltage & Resistor

Solartron 7150
Precision resistor for computer input (250)

Outlined procedure for differential pressure

The calibration procedure for differential pressure transmitter includes 5 different tests.

Onshore (test lab)

1) Atmospheric test

This test includes verification of differential

range at atmospheric pressure. The objective is to monitor calibration shift between onshore testing. No adjustments.

2) Calibration at static pressure

The transmitter is calibrated at operational static pressure. Adjustments may be performed.

3) "Footprint test"

A "footprint" of the transmitter's range at atmospheric pressure is recorded.

NB: No adjustment is performed.

Offshore

1) Offshore "footprint" verification test

This includes a verification of the transmitter's "footprint" established onshore. This is done after the transmitter is installed.

The objective is to verify that no calibration shift has occurred during transportation from shore to platform.

If the "footprint" test is completed and results are within the set tolerance the transmitter is put in use.

2) Offshore "footprint" as found test

The test includes a verification of the transmitter's "footprint" after it has been used in process.

The objective with the test is to monitor output stability.

This test completes the period for the transmitter and it will be sent to shore for testing as stated under previous paragraph.

Testing is performed at 5 different points over the transmitter's range.

Outlined procedure for static pressure transmitters

These transmitters are calibrated offshore only (installed in the process).

Equipment

Pressure reference

AMETEK DWT (hydraulic).

Voltage measurement

Solartron 7150.

Procedure

Pressure is applied to the transmitter with the dead weight tester and transmitter output is measured in the control room across a 250 precision resistor at flowcomputer input.

Testing is performed at 5 different points over the transmitter's range.

4. PRACTICAL EXPERIENCE FROM APPLICATION OF ST3000

4.1 Application area

4.1.1 Process parameters and installation

Honeywell ST3000 transmitters are utilized in fiscal gas metering stations for measurement of differential pressure (DP) and line pressure in orifice meter runs.

Fiscal metering of gas on the Statfjord field includes 4 metering stations.

	No ST3000 DP	No ST3000 Line Pressure	Capacity of Station Approx (MSm ³ /D)
Statfjord "A"	6	3	7.67
Statfjord "B" Statpipe	4	2	5.5
Statfjord "B" UK-Offtake	4	2	3.0
Statfjord "C"	4	2	5.5

The flow measurement is performed in accordance with ISO 5167.

The applied ranges and estimated uncertainty for the transmitters are listed in table 1. Differential pressure measurement across the orifice plate is performed with two transmitters per meter run.

Table 1

	Range	Est. Uncertainty(%)
DP Transmitter A	0-100 mbar	0.3
DP Transmitter B	0-500 mbar	0.2
Line pressure transmitter	0-250 bar	0.25

4.2 Results from testing of transmitters

Prior to start up of Gas Sales from Statfjord the Operator (Mobil Exploration) performed a market survey in 1983 in order to select a high quality differential pressure transmitter. The uncertainty of measurement was emphasized and was considered to be the major checkpoint.

Honeywell supplied 3 ST3000 transmitters for testing.

The main objective with this test was to verify the manufacturers uncertainty specification including the output shift with varying static pressure.

4.2.1 Conclusion from market survey

The test revealed problems for one of the ST3000 test objects; it was found to be outside manufacturers specification.

However, the overall evaluation of the transmitters main features concluded that a cooperation should be established with Honeywell. The test objects were of the very first generation and further testing convinced us that we should choose ST3000 for the gas metering stations.

4.2.2 Test results from ambient temperature effect on DP measurement

In order to verify ambient temperature effect on differential pressure measurement it was decided to test 4 ST3000 DP-transmitters at various ambient temperatures.

Test Arrangement

The four transmitters were located in a thermal test chamber.

Pressure was applied (differential pressure over the transmitters range at a given static pressure) from a common pressure source. Transmitter output values were monitored with a digital voltmeter hooked up across a 250 resistor.

Monitoring of temperature in chamber was performed with a thermo couple probe.

All test instruments have traceability to National Standards (UK).

Test procedure and objectives

The objective was to evaluate the transmitter measurement results over the temperature range of 0°C - 75°C at differential spans of 100, 200, 500 and 1000 mbar.

Calibration of transmitters were performed at room temperature and at 140 bar and atmospheric pressure. The upper range values were set before commencing the test at the four differential pressure spans.

Transmitters were exposed to 4 different ambient temperatures; nominal values: 0°C, 20°C, 50°C and 75°C.

The transmitters output results were recorded at each of the temperatures and at static pressures of 140 bar and atmospheric for the applied differential pressures over the range at 0%, 25%, 50%, 75%, 100% and 110% and the same testpoints down. This was done for all 4 spans.

Please refer to attached graphs (Fig. 3-6). Nominal testpoints were:

1, 2, 3, 4, 5 volts

Output signal was measured across a 250 resistor.

The discrepancies from the ideal value is presented in bar diagram.

We have attached results only for 2 transmitters from 4 tests.

Conclusion

Severe leakage problems in process head were revealed at 0°C ambient temperature with three transmitters. The torque setting of the bolts were checked and the problem was rectified.

The manufacturers excuse to this problem was explained with the torque setting during the assemblance at the factory. Their quality assurance/quality control system obviously needed some improvement.

1 transmitter failed at a temperature in excess of 50°C.

With these described failures in mind users start to ask questions about the quality of the cells.

All our cells were checked for correct torquesetting and pressure tested (a calibration verification).

The ambient temperature in our application will most likely not exceed 50°C, so the overall conclusion will be based on the tests below 50°C.

If we exclude the leakage problem and failure for 1 cell at 75% the overall results from the test is good and may be summarized with the following values:

In general the temperature effect was better than + 0.2% of calibrated range for a temperature range of 50°C. However, one cell indicated output within ± 0.3 of span over the same temperature range.

This test verified that the quoted estimated uncertainty in DP measurement was achievable.

4.2.3 Test performed by other laboratories

Other independent test laboratories have performed testing on the ST3000 and the general conclusion is that the cells operates within manufacturers specification.

4.2.4 Stability in calibration

Ref. fig. 7-12, table 2 and calibration procedures.

The attached graphs represents comparison in test results from onshore calibration at static pressure and the "footprint" of the transmitter from one period to the next.

The results are presented as difference in output in % of span from one period to the next.

Two DP-cells and one gauge pressure transmitter are included in this presentation. These are typical for the transmitters in operation on Statfjord.

Conclusion

The transmitters have proven to be extremely stable in calibration. We have therefore reduced maintenance cost since the calibration intervals have so far been increased from every month to every second month, and foresee 3 monthly intervals in the future.

Table for transmitter monitoring:

Table 2

	<u>Range</u>	<u>Ser. no.</u>	<u>Time in use</u>	<u>No. of Tests</u>	<u>No. of Adjustm.</u>
DP Transmitter A	0-500 mbar	8525-004	Aug 85-Apr 87	8	1 at zero
DP Transmitter B	0-100 mbar	8511-020	Jul 85-Apr 87	7	1 at zero of span
P Transmitter C	0-250 bar	8510-031	8 months	8	None

4.2.5 Reliability and availability

After approximately 2.5 years months in operation with ST3000 we have had no downtime due to transmitter failures.

The transmitters have proven to be very reliable and based on our experience the availability rating is very high.

4.3. Summary and general conclusion for field experience

We faced some problems during the early stages of ST3000 applications and over the time the communication with the Honeywell vendor contained some negative statements concerning the quality of the transmitters.

However, these problems were resolved and the cooperation have been very good.

Comparing the transmitter with conventional instruments it was certainly a great improvement within process measurement field.

The transmitters have proven to be user friendly, reliable and the stability in calibration is very good.

The present calibration concept is under evaluation and based on the good quality of the instruments the calibration procedure may be simplified.

5 FUTURE TRENDS IN PROCESS MEASUREMENT

The future trends within the transmitter field indicates several new important developments. To our knowledge Honeywell was the first manufacturer who released transmitters with the smart concept. Since then other manufacturers have introduced transmitters with similar specifications.

For the pressure measurement the trend seem to divert into application of quartz crystal in standard field instruments for the process industry.

Application of microprocessors require digital techniques. Transmission from field to control room is performed via an analog signal. This requires D/A and A/D converters.

The new systems includes the option of digital transmission and thereby improves overall loop uncertainty.

Application of "intelligence" (microprocessors) in the primary elements is a very important improvement and is utilized for a number of different process parameter measurement. In future applications this concept will be applied to a large extent.

This will improve measurements and probably contribute to lower maintenance cost.

Specifications

Operating Conditions

	Reference Condition	Rated Condition	Operative Limits	Transportation and Storage
Ambient Temperature	°C 25 ± 1 °F 77 ± 2	- 40 to 85 - 40 to 185	- 40 to 93.3 - 40 to 200	- 55 to 125 - 67 to 257
Meter Body Temperature	°C 25 ± 1 °F 77 ± 1	- 40 to 110* - 40 to 230	- 40 to 125 - 40 to 257	- 55 to 125 - 67 to 257
Humidity	% 10-55	—	0-100	—
Supply Voltage and Load Resistance	See Figure 2.			
Overpressure	psi 0	3000 psi	3000 psi	
In Vacuum Region	mm Hg Abs atmospheric	atmospheric to 25	atmospheric to 2	

Performance Under Rated Conditions

Upper Range Limit	400 inches H ₂ O
Turndown Ratio	400:1
Minimum Span	1 in H ₂ O
Zero Elevation and Suppression	Regardless of output specified, zero elevation and suppression must be such that neither the span nor the upper or lower range value exceed 100% of the upper range limit. 4-20 mA dc maximum elevation: 40,000% of calibrated span. Maximum zero suppression: 39,900% of calibrated span.
Accuracy (Reference) (Includes combined effects of linearity, hysteresis, and repeatability)	± 0.1% of calibrated span or upper range value, whichever is greater, terminal based. NOTE: Below 50 in H ₂ O accuracy equals $0.05 + \left(0.05 \times \frac{50 \text{ in H}_2\text{O}}{\text{span in H}_2\text{O}}\right)$
* Combined Zero and Span Temperature Effect per 28°C (50°F)	± 0.25% of calibrated span, between reference span and Upper Range Limit. NOTE: Below 50 in H ₂ O accuracy equals $0.2 + \left(0.05 \times \frac{50 \text{ in H}_2\text{O}}{\text{span in H}_2\text{O}}\right)$
* Combined Zero and Span Static Pressure Effect per 1000 psi	± 0.2% of the calibrated span, between reference span and Upper Range Limit. NOTE: Below 100 in H ₂ O accuracy equals $0.2 \left(\frac{100 \text{ in H}_2\text{O}}{\text{span in H}_2\text{O}}\right)$
Hysteresis % of Span	0.02
Output (two-wire)	4 to 20 milliamps
Supply Voltage Effect	0.005% of span
Damping Time Constant	Adjustable from 0 to 32 seconds
RFI Protection (Standard)	20 to 1000 MHz at 30 volts per meter

Physical

Materials	
Process Interface	<i>Process Barrier Diaphragms:</i> 316 S.S., Hastelloy C-276, Monel <i>Process Head:</i> 316 S.S., Carbon Steel, Monel, Hastelloy <i>Head Gaskets:</i> Teflon <i>Bolting:</i> Carbon steel, 17-4 PH stainless steel
Mounting Bracket	Carbon Steel (zinc plated)
Fill Fluid	Silicone oil or fluorolube
Electronic Housing	Low Copper Aluminum Meets NEMA 4 (watertight) and NEMA 7 (explosion-proof)
Process Connections	1/4 inch NPT (optional 1/4 inch PT)
Wiring	Accepts up to 16 AWG (1.5 mm diameter)
Mounting	See Figure 3.
Dimensions	See Figure 4.
Net Weight	7 Kg (15.4 pounds)
Hazardous Conditions	Designed to meet requirements of explosion-proof and intrinsically safe systems for North American classifications Class I, Group A, B, C, and D, Division I and European EEX, Ia, II, C, T6. Contact Fort Washington for approval body codes

*For fluorolube fill fluid, the rating is - 15 to 110°C (5 to 230°F).

ST 3000 DIFFERENTIAL PRESSURE TRANSMITTER
1987 SPECIFICATION

Specifications

Operating Conditions

	Reference Condition	Rated Condition	Operative Limits	Transportation and Storage
Ambient Temperature	°C 25 ± 1 °F 77 ± 2	-40 to 85 -40 to 185	-40 to 93 -40 to 200	-55 to 125 -67 to 257
Meter Body Temperature	°C 25 ± 1 °F 77 ± 1	-40 to 110* -40 to 230	-40 to 125 -40 to 257	-55 to 125 -67 to 257
Humidity	% 10-55	0-100	0-100	0-100
Supply Voltage and Load Resistance	(See Figure 2.)			
Overpressure	psi 0	3000 psi (210 bar)	3000 psi (210 bar)	
In Vacuum Region (Min Press.)	mm Hg Abs atmospheric	25	2 (Short term)	

Performance Under Rated Conditions

Upper Range Limit	400 in H ₂ O (1000 mbar)
Turndown Ratio	400:1
Minimum Span	1 in H ₂ O (2.5 mbar)
Zero Elevation and Suppression	No limit (except minimum span) within ±100% URL. Specifications valid from -5% to +100% URL.
Accuracy (Reference) (Includes combined effects of linearity, hysteresis, and repeatability)**†	<p><i>Analog Mode</i> : ±0.10% calibrated span or upper range value (URV), whichever is greater, terminal based.</p> <p>For URV below reference span (25 in H₂O) accuracy equals :</p> $0.05 + \left(0.05 \times \frac{25 \text{ in H}_2\text{O}}{\text{span in H}_2\text{O}}\right) \text{ or } 0.05 + \left(0.05 \times \frac{62 \text{ mbar}}{\text{span mbar}}\right) \text{ in \% span}$ <p><i>Digital Mode</i> : ±0.075% span / ±0.15% reading</p> <p>See Digital Communications Mode Specification 34-ST-03-27 for explanations of transmitter accuracy and system accuracy.</p>
Combined Zero and Span Temperature Effect per 28°C (50°F)**	<p><i>Analog Mode</i> : ±0.175% of span.</p> <p>For URV below reference span (50 in H₂O) effect equals :</p> $0.125 + \left(0.05 \times \frac{50 \text{ in H}_2\text{O}}{\text{span in H}_2\text{O}}\right) \text{ or } 0.125 + \left(0.05 \times \frac{125 \text{ mbar}}{\text{span mbar}}\right) \text{ in \% span}$ <p><i>Digital Mode</i> : ±0.125% reading</p> <p>For readings below reference span (50 in H₂O) effect equals :</p> $0.075 + \left(0.05 \times \frac{50 \text{ in H}_2\text{O}}{\text{rdg in H}_2\text{O}}\right) \text{ or } 0.075 + \left(0.05 \times \frac{125 \text{ mbar}}{\text{rdg mbar}}\right) \text{ in \% reading}$
Combined Zero and Span Static Pressure Effect per 1000 psi	<p><i>Analog Mode</i> : ±0.2% of span, except 0.2 in H₂O (0.5 mbar) minimum. Typical performance is ±0.1%, except 0.06 in H₂O (0.15 mbar) minimum with stainless steel diaphragms.</p> <p><i>Digital Mode</i> : Same except in % reading</p>
Output (two-wire)	4 to 20 milliamps, or digital communications mode
Supply Voltage Effect	0.005% of span per volt
Damping Time Constant	Adjustable from 0 to 32 seconds digital damping
RFI Protection (Standard)	Negligible effect (20 to 1000 MHz at 30 volts per meter)

Physical

Materials	
Process Interface	<p><i>Process Barrier Diaphragms</i> : 316L SS, Hastelloy C-276, Monel, Tantalum</p> <p><i>Process Head</i> : 316 SS, Carbon Steel, Monel, Hastelloy</p> <p><i>Head Gaskets</i> : Teflon, Viton</p> <p><i>Bolting</i> : Carbon steel, A-286 SS (NACE)</p>
Mounting Bracket	Carbon Steel (zinc plated)
Fill Fluid	Silicone oil or CTFE (chlorotrifluoroethylene)
Electronic Housing	Low Copper Aluminium Meets NEMA 4 (watertight) and NEMA 7 (explosion-proof)
Process Connexions	1/4 inch NPT (optional 1/2 NPT with adapter)
Wiring	Accepts up to 16 AWG (1.5 mm diameter)
Mounting	(See Figure 3.)
Dimensions	(See Figure 4.)
Net Weight	7 Kg (15.4 pounds)
Hazardous Conditions	Designed to meet requirements of explosion-proof and intrinsically safe systems for North American classifications Class I, Groups A, B, C and D, Division (explosion-proof systems, Groups B, C, D only), European (CENELEC) EEX, ia, IIC, T6 and BASEEFA Type N.

* For CTFE fill fluid, the rating is -15 to 110°C (5 to 230°F).

** Specification does not apply to ST 3000 with tantalum barrier diaphragms.

† Accuracy includes residual error after averaging successive readings.

Specifications**Operating Conditions**

	Reference Condition	Rated Condition	Operative Limits	Transportation and Storage
Ambient Temperature	°C 25 ± 1 °F 77 ± 2	- 40 to 85 - 40 to 185	- 40 to 93.3 - 40 to 200	- 55 to 125 - 67 to 257
Meter Body Temperature	°C 25 ± 1 °F 77 ± 1	- 40 to 110* - 40 to 230*	- 40 to 125 - 40 to 257	- 55 to 125 - 67 to 257
Humidity	% 10-55	10-90	0-100	
Supply Voltage and Load Resistance	See Figure 2.			
Overpressure	psi 0	9,000 psi (620 bar)	9,000 psi (620 bar)	
In Vacuum Region	mm Hg Abs atmospheric	atmospheric to 25	atmospheric to 2	

Performance Under Rated Conditions

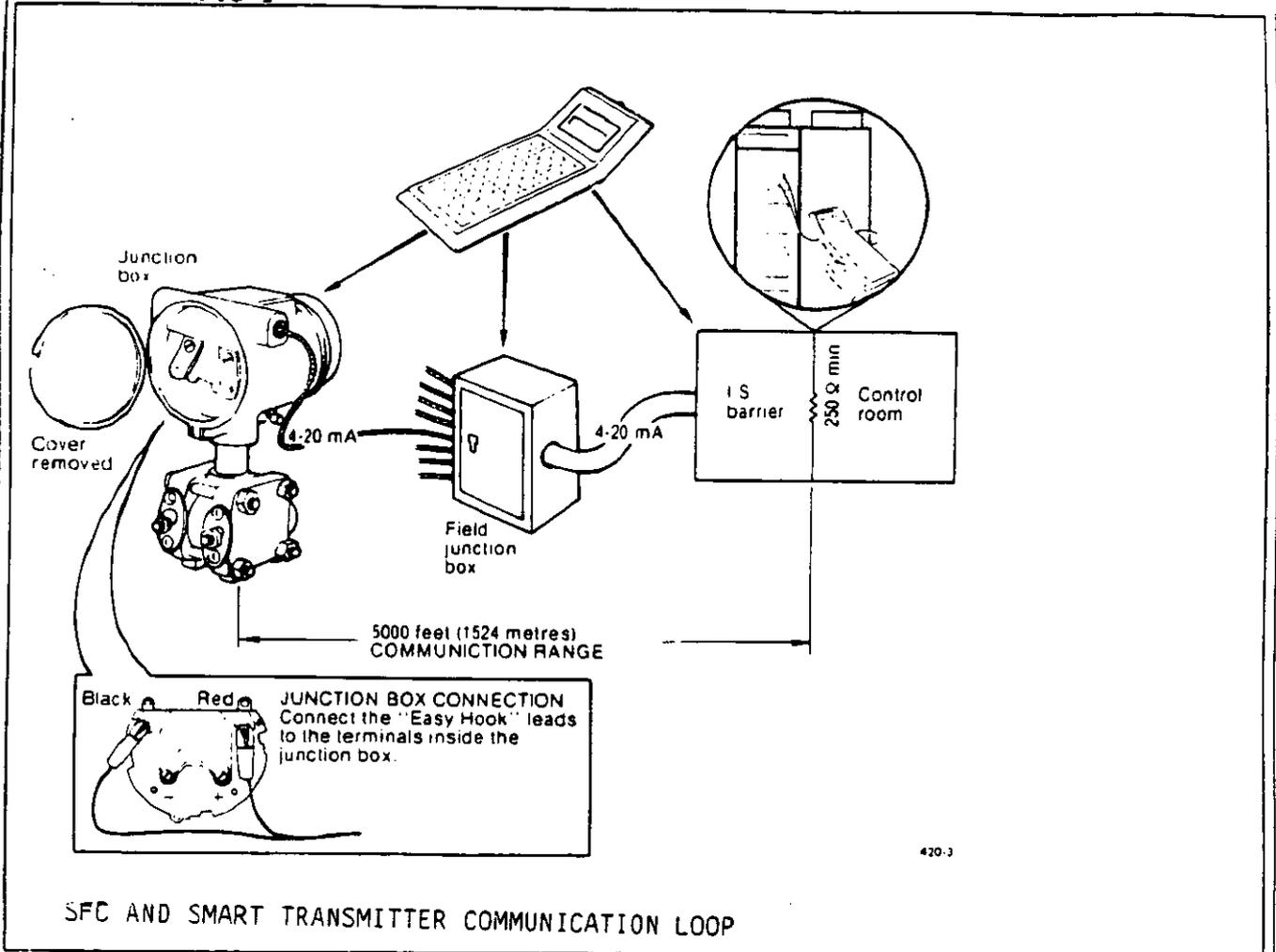
Upper Range Limit	6,000 psi (415 bar)
Turndown Ratio	60:1
Minimum Span	100 psi (7 bar)
Zero Elevation and Suppression	Regardless of output specified, zero elevation and suppression must be such that neither the span nor the upper or lower range value exceed 100% of the upper range limit. Maximum Zero Elevation: 14.7% of calibrated span. Maximum zero suppression: 5,900% of calibrated span.
Accuracy (Reference) (includes combined effects of linearity, hysteresis, and repeatability)	± 0.15% of calibrated span or upper range value, (URV) whichever is greater, terminal based. NOTE: For URV below 1000 psi accuracy equals $0.10 + \left(0.05 \times \frac{1000 \text{ psi}}{\text{span in psi}}\right) \quad \text{or} \quad 0.10 + \left(0.05 \times \frac{70 \text{ bar}}{\text{Span in bar}}\right)$
Combined Zero and Span Temperature Effect per 28°C (50°F)	0.25% of calibrated span. NOTE: For URV below 1000 psi effect equals $0.2 + \left(0.05 \times \frac{1000 \text{ psi}}{\text{span in psi}}\right) \quad \text{or} \quad 0.2 + \left(0.05 \times \frac{70 \text{ bar}}{\text{Span in bar}}\right)$
Output (two-wire)	4 to 20 milliamps
Supply Voltage Effect	0.005% of span per volt
Damping Time Constant	Adjustable from 0 to 32 seconds digital damping
RFI Protection (Standard)	Negligible (20 to 1000 MHz at 30 volts per meter)

Physical

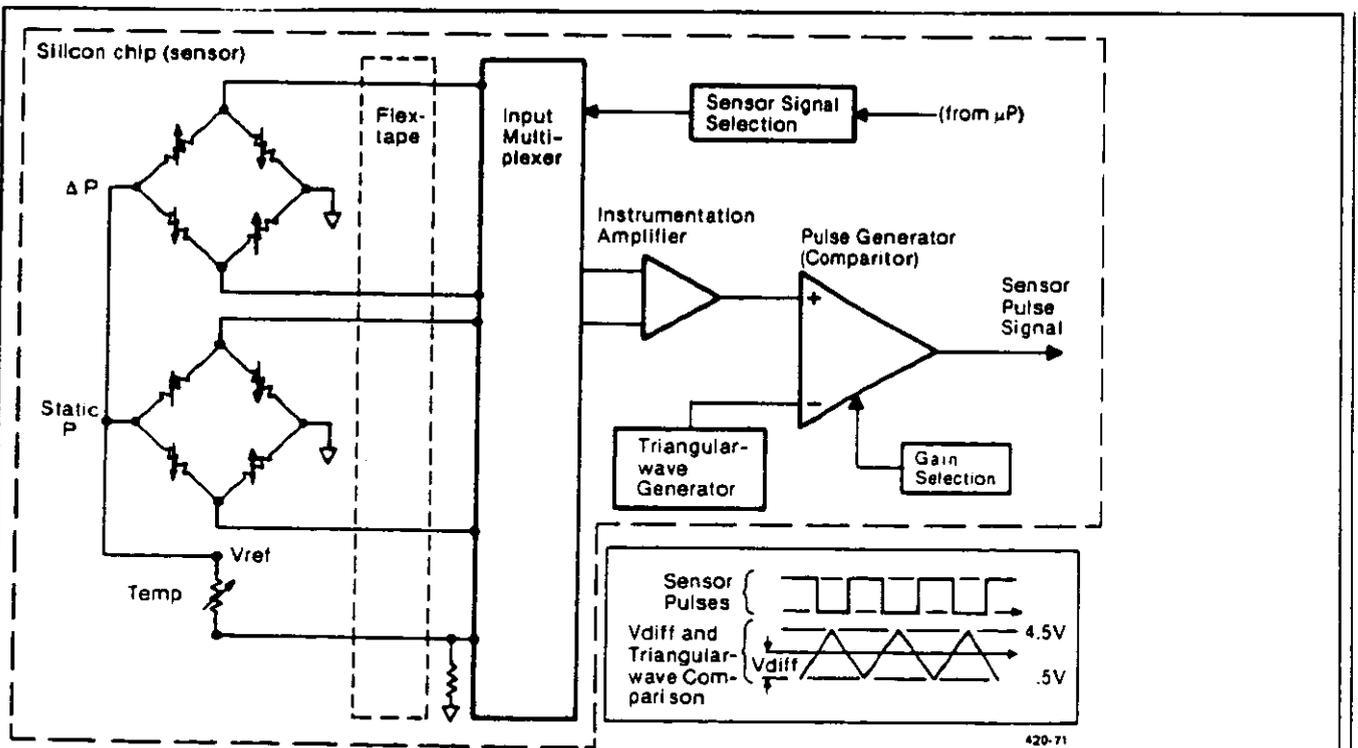
Materials	
Process Interface	<i>Process Barrier Diaphragms:</i> 316L S.S., Hastelloy C-276, Monel <i>Process Head:</i> 316 S.S., Carbon Steel <i>Head Gaskets:</i> Teflon, Viton <i>Bolting:</i> Carbon steel, 17-4 PH stainless steel
Mounting Bracket	Carbon Steel (zinc plated)
Fill Fluid	Silicone oil or fluorolube
Electronic Housing	Low Copper Aluminum Meets NEMA 4 (watertight) and NEMA 7 (explosion-proof)
Process Connections	1/2 inch NPT
Wiring	Accepts up to 16 AWG (1.5 mm diameter)
Mounting	See Figure 3.
Dimensions	See Figure 4.
Net Weight	6.5 Kg (14 pounds)
Hazardous Conditions	Designed to meet requirements of explosion-proof and intrinsically safe systems for North American classifications Class I, Group A, B, C, and D, Division I and European (CENELEC) EEX, ia, IIC, T6. Contact Fort Washington for approval body codes.

*For Fluorolube fill fluid the rating is - 15 to 110°C (5 to 230°F).

FIG 1



SFC AND SMART TRANSMITTER COMMUNICATION LOOP



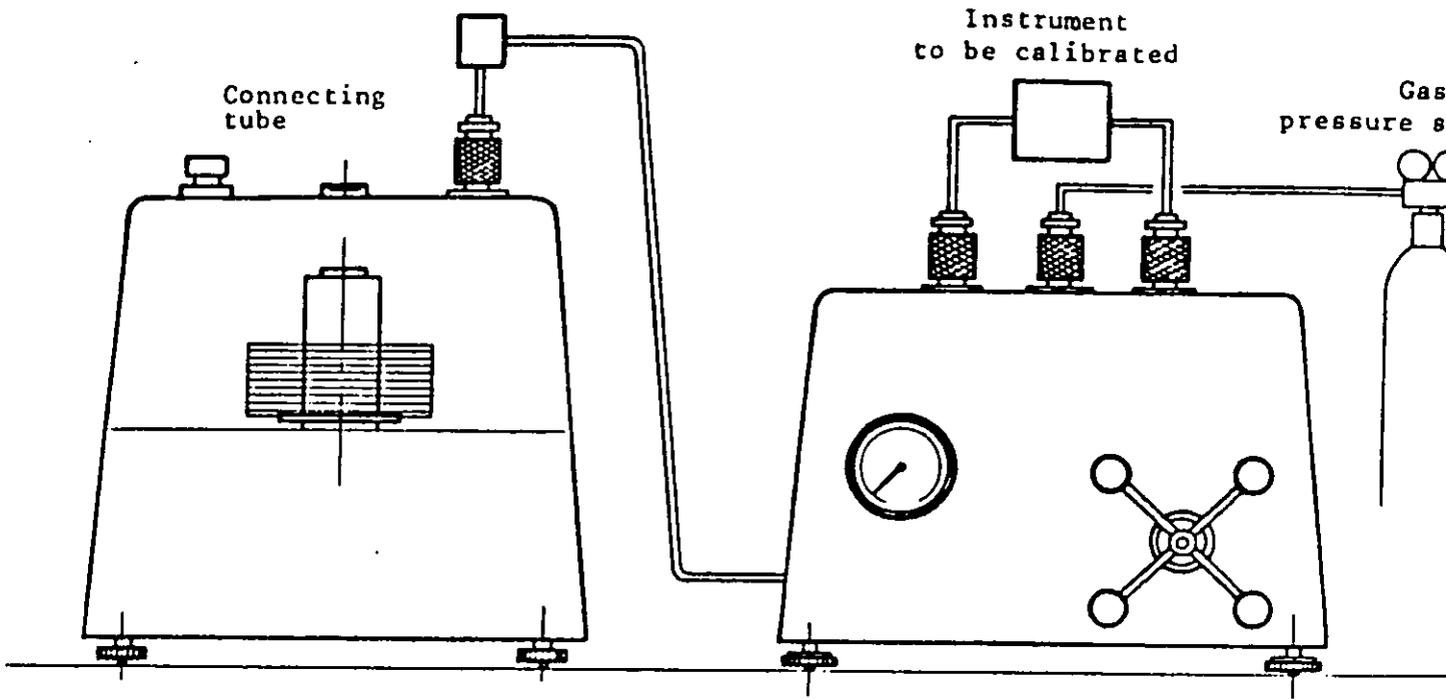
SENSOR SIGNAL SELECTION AND A/D CONVERSION

Schematic

1) PRESSURE

DIVIDER MODEL 1500

Installation Schematic

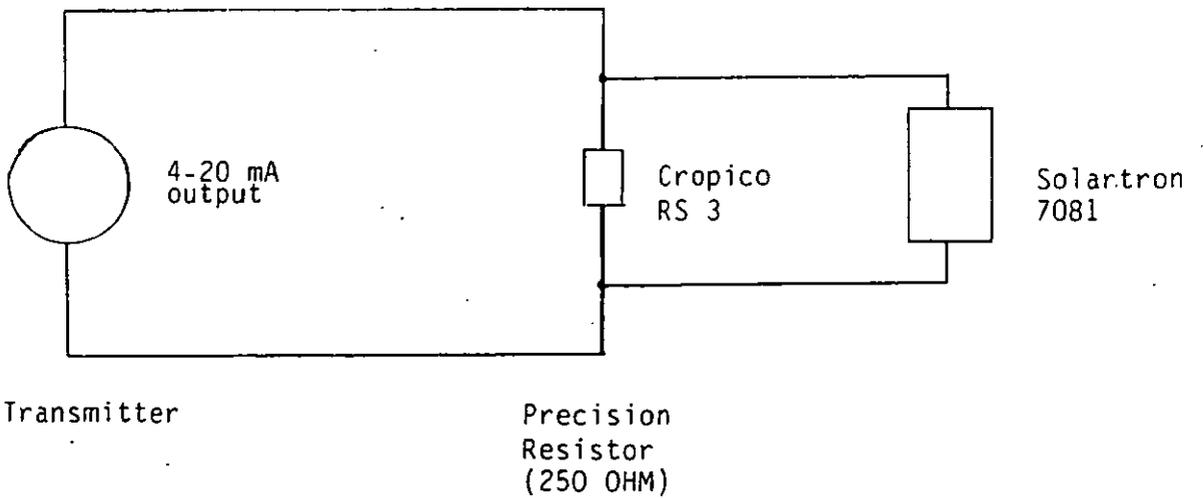


Oil-operated standard Type 5300

Divider Model 1500

2) ELECTRICAL

+ POWER SUPPLY



Calibration hook-up fig.

THERMAL TESTS ON HONEYWELL TRANSMITTER.

Pressure: 140 bar, DP range: 0-500 mbar

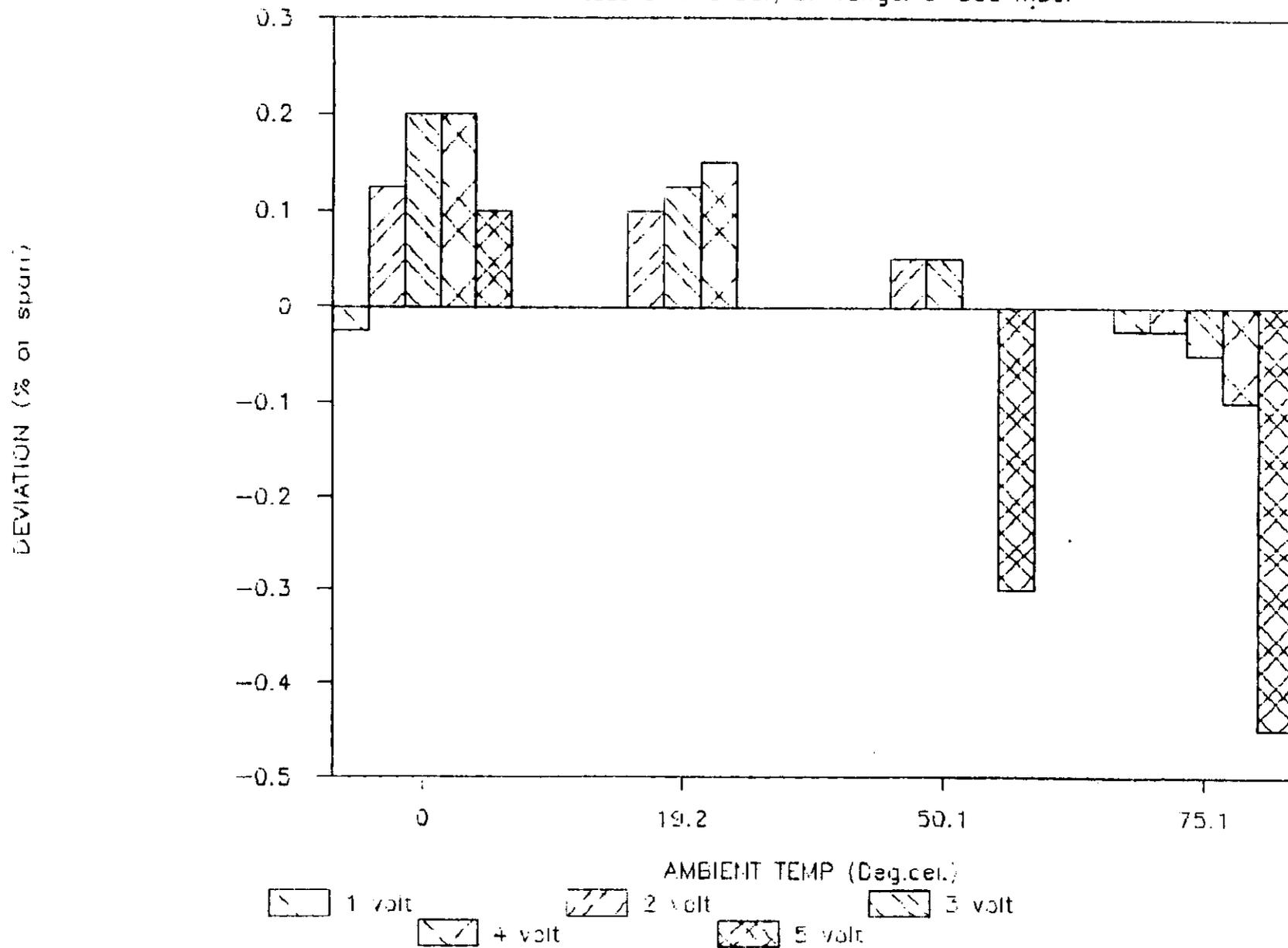


FIG 3

SER. NO: 8525-008

THERMAL TESTS ON HONEYWELL TRANSMITTER.

Pressure: 140 bar. DP range: 0-100 mbar

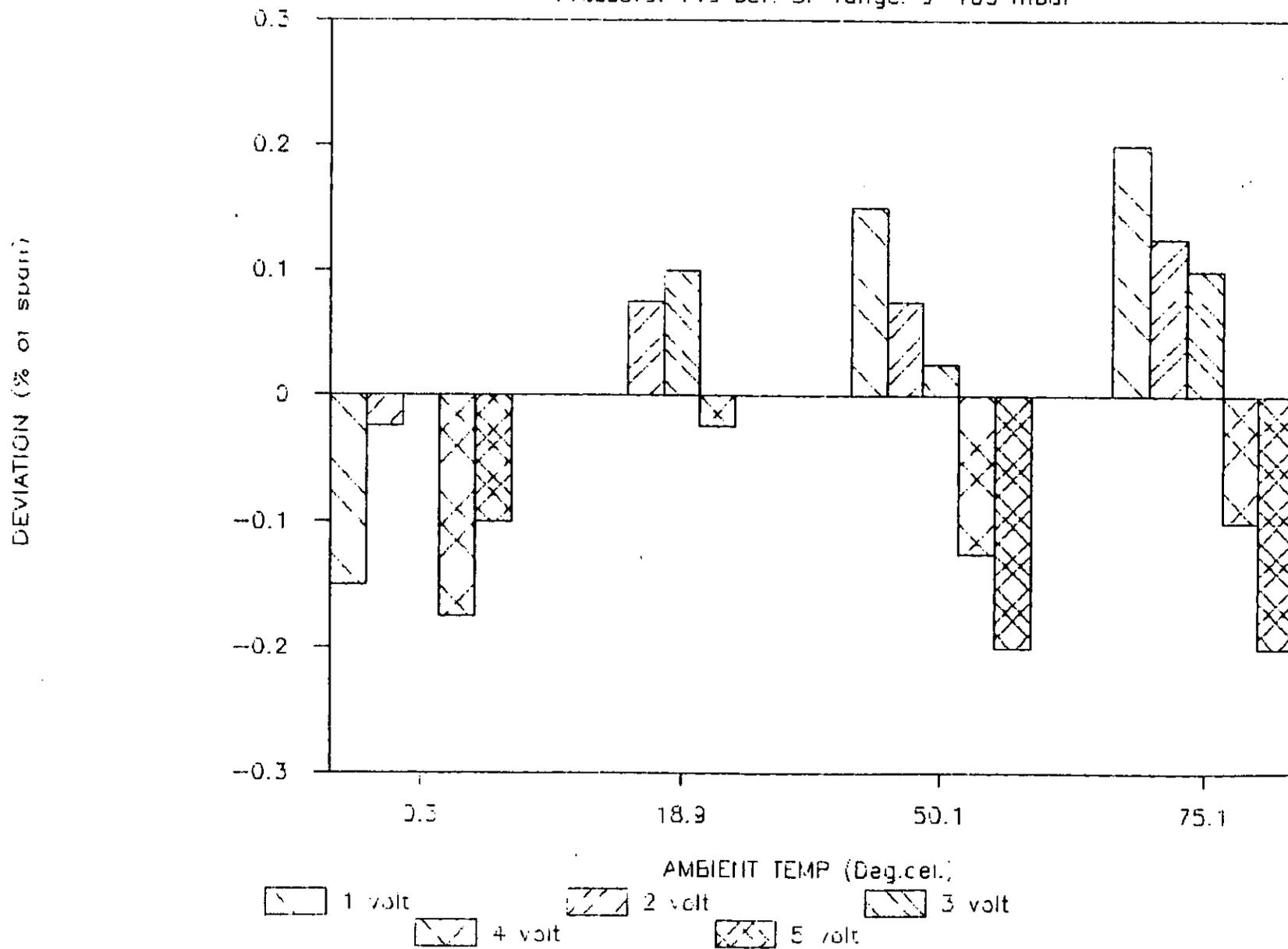


FIG.4

SER.NO:8525-008

THERMAL TESTS ON HONEYWELL TRANSMITTER

Pressure: Atm. , DP range: 0-100 mbar

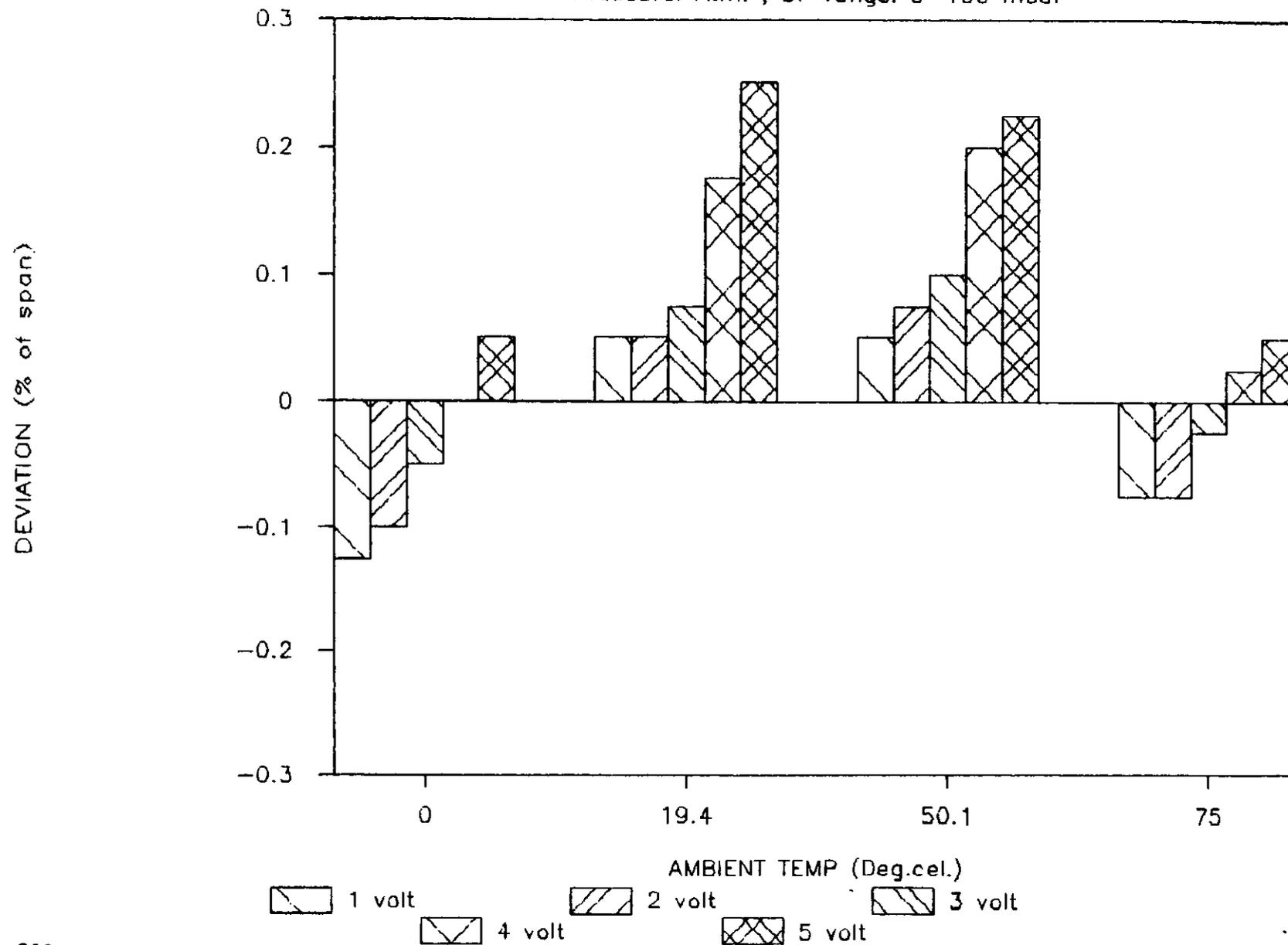


FIG5

SER. NO: 8511-003

THERMAL TESTS ON HONEYWELL TRANSMITTER

Pressure: Atm. , DP range: 0-500 mbar

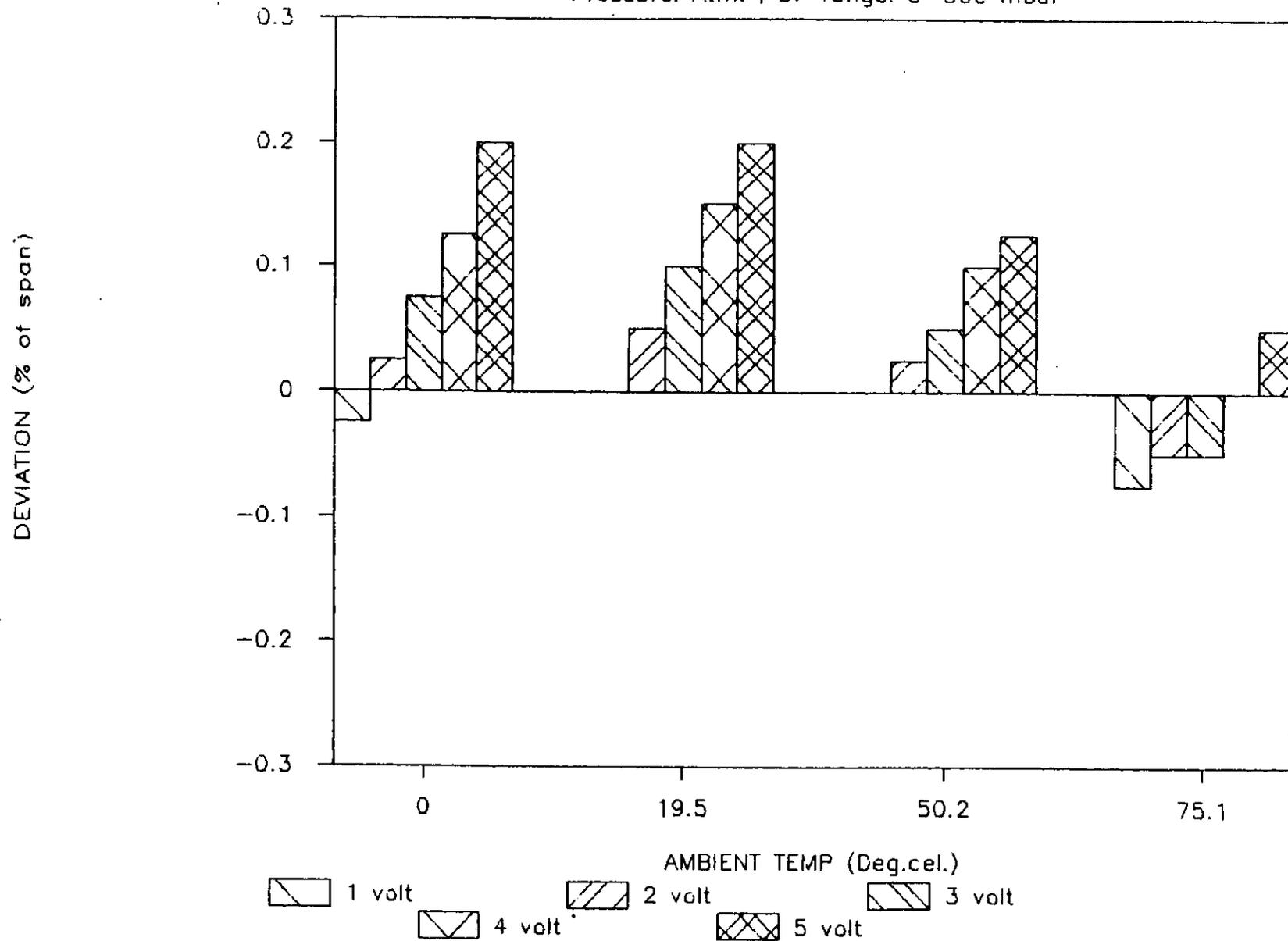


FIG 6

SER.NO:8511-003

FISCAL METERING - TEST SERIES
OVERVIEW ONE CYCLE
DP-TRANSMITTER
HONEYWELL SMART

ONSHORE STATIC PRESSURE TEST/CALIBRATION
ONSHORE FOOTPRINT TEST
OFFSHORE FOOTPRINT TEST
OFFSHORE AS FOUND FOOTPRINT TEST

ONSHORE ATMOSPHERIC TEST
ONSHORE STATIC PRESSURE TEST/CALIBRATION
ONSHORE FOOTPRINT TEST
OFFSHORE FOOTPRINT TEST
OFFSHORE AS FOUND FOOTPRINT TEST
ONSHORE ATMOSPHERIC TEST

START PERIOD

1. PERIOD

2. PERIOD

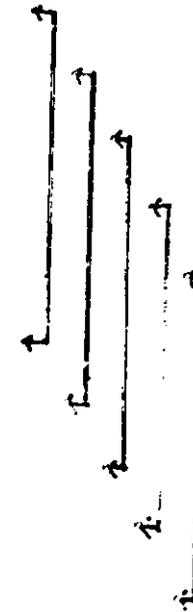


FIG 7

DEVIATION IN %
OF SPAN

HONEYWELL SMART 3000

DIFFERENTIAL PRESSURERANGE: 0- 500 mbar

Serial no 8525 - 004

Onshore Footprint Test

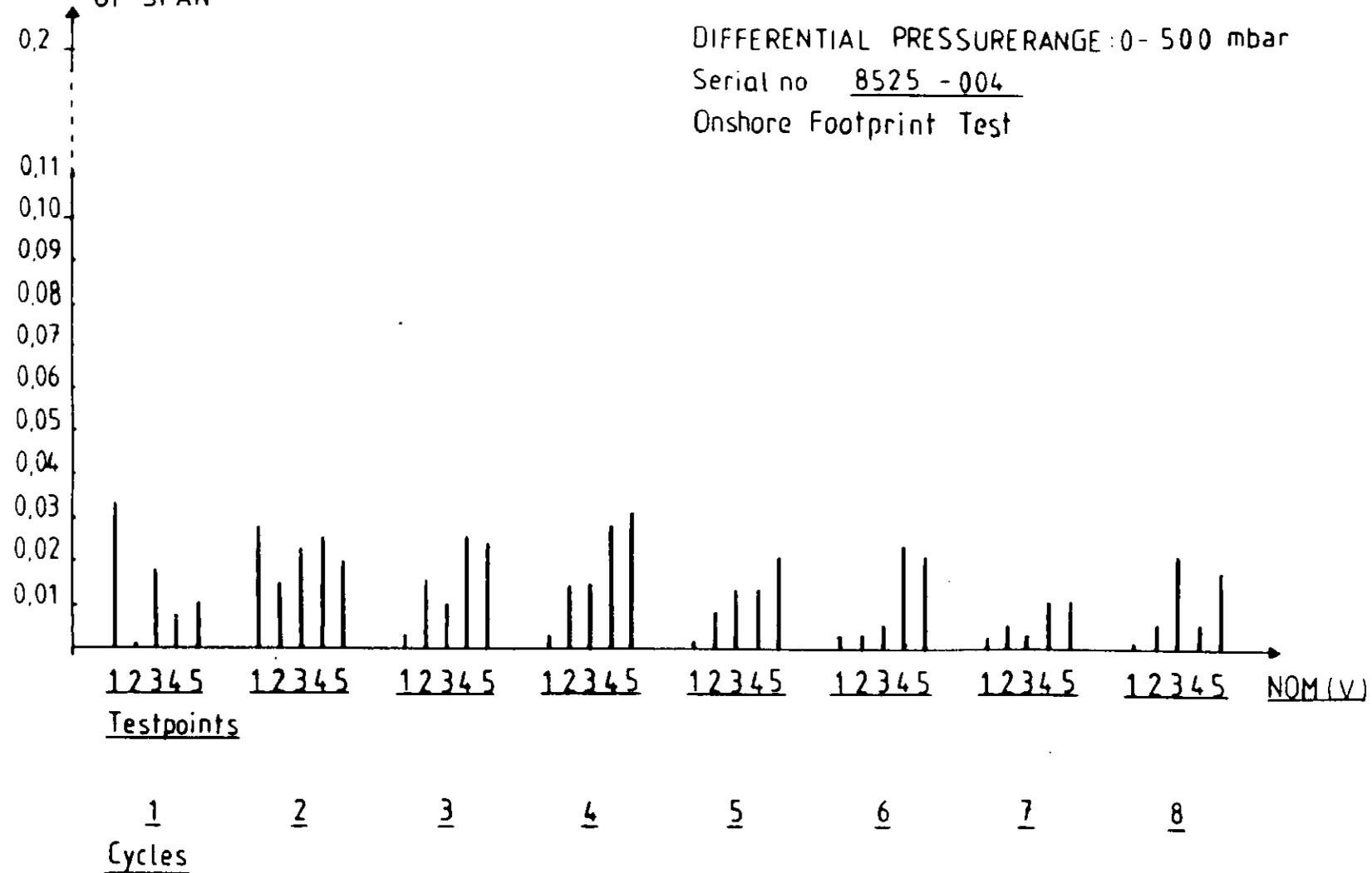


FIG. 8

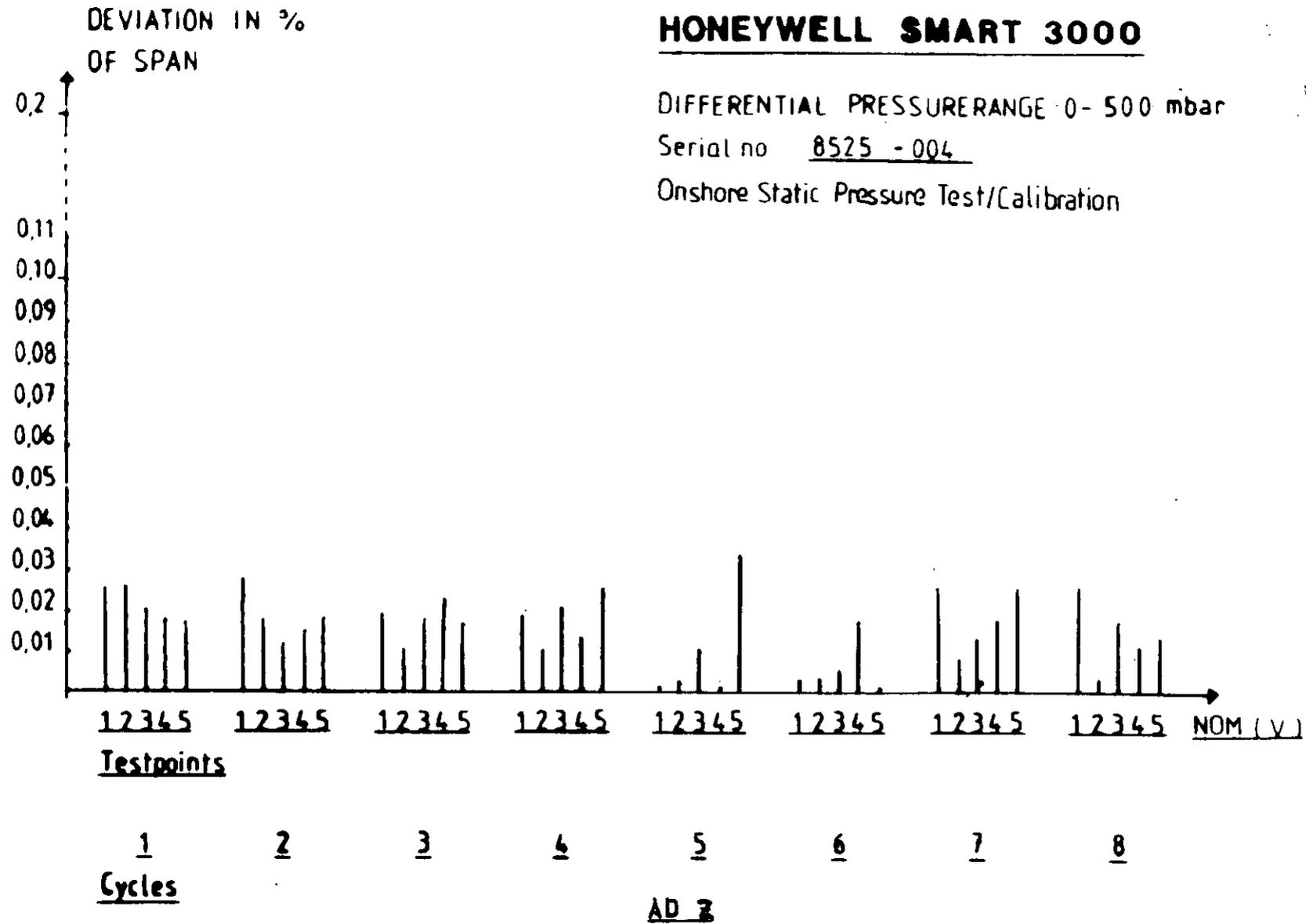


FIG 9

DEVIATION IN %
OF SPAN

HONEYWELL SMART 3000

DIFFERENTIAL PRESSURERANGE: 0- 100 mbar

Serial no: 8511 - 020

Onshore Footprint Test

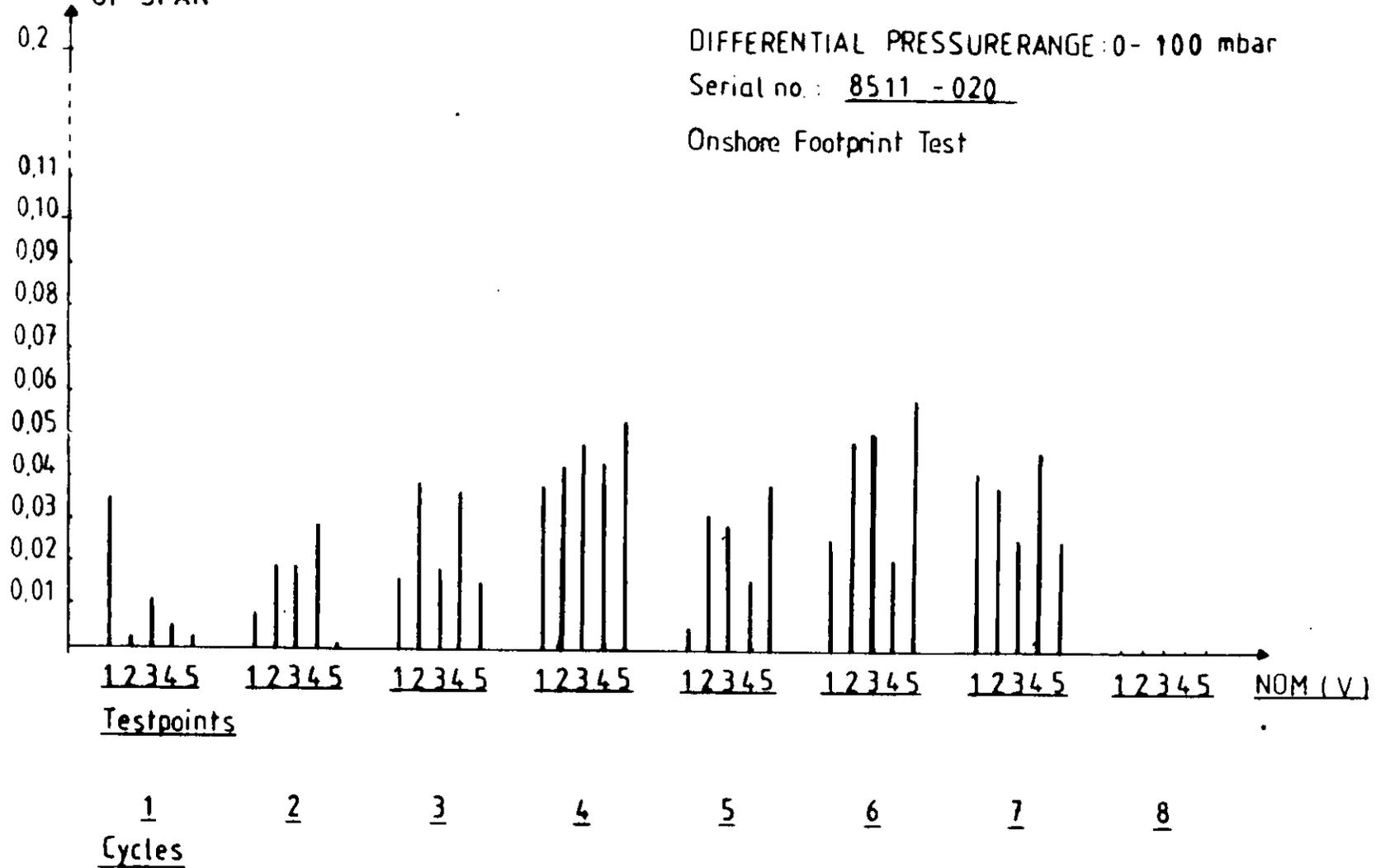


FIG 10

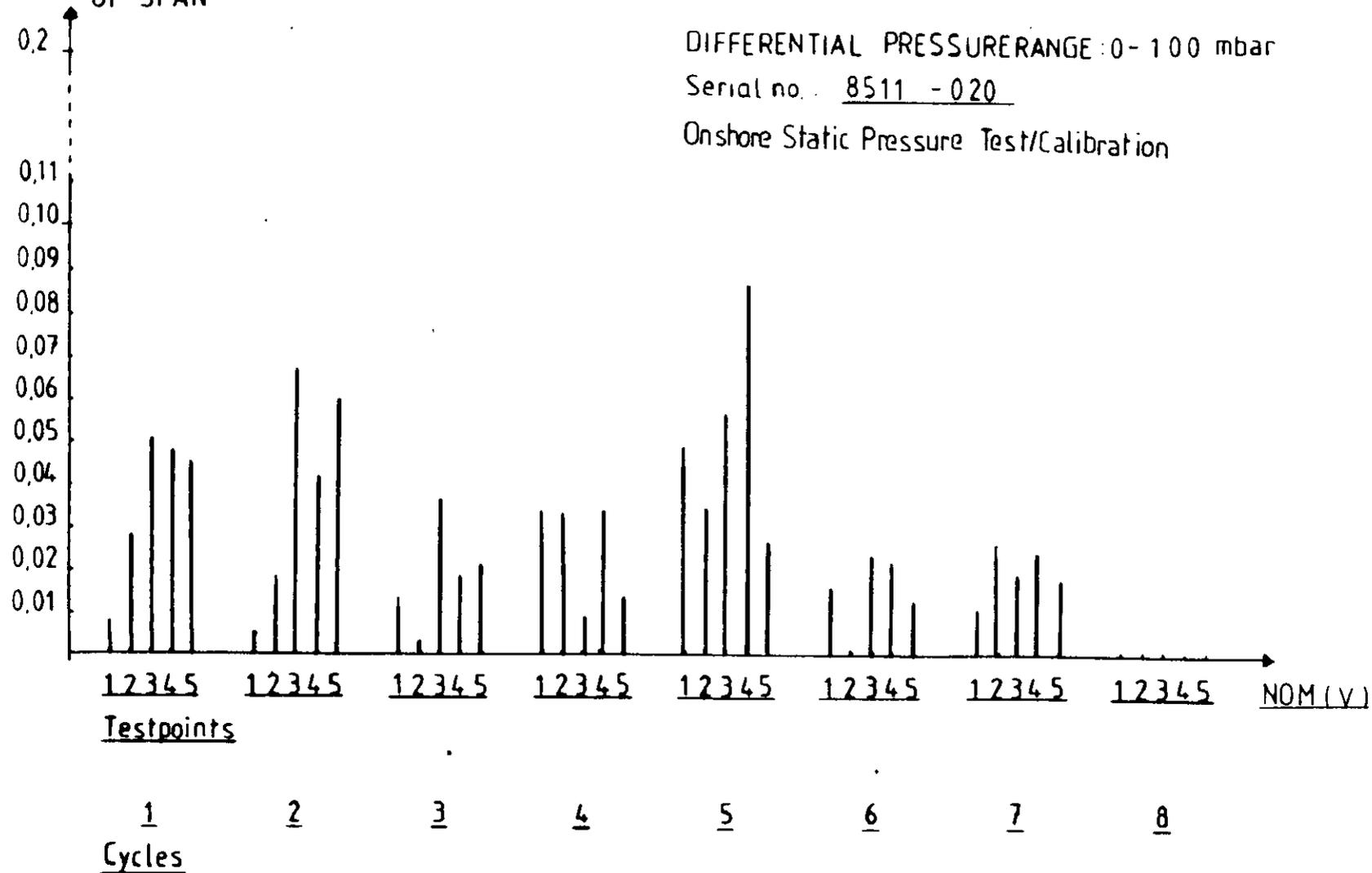
DEVIATION IN %
OF SPAN

HONEYWELL SMART 3000

DIFFERENTIAL PRESSURERANGE: 0-100 mbar

Serial no. 8511 - 020

Onshore Static Pressure Test/Calibration



ADZ-S

FIG 11

HONEYWELL SMART 3000

PRESSURERANGE : 0- 250 bar

Serial no : 8510-031

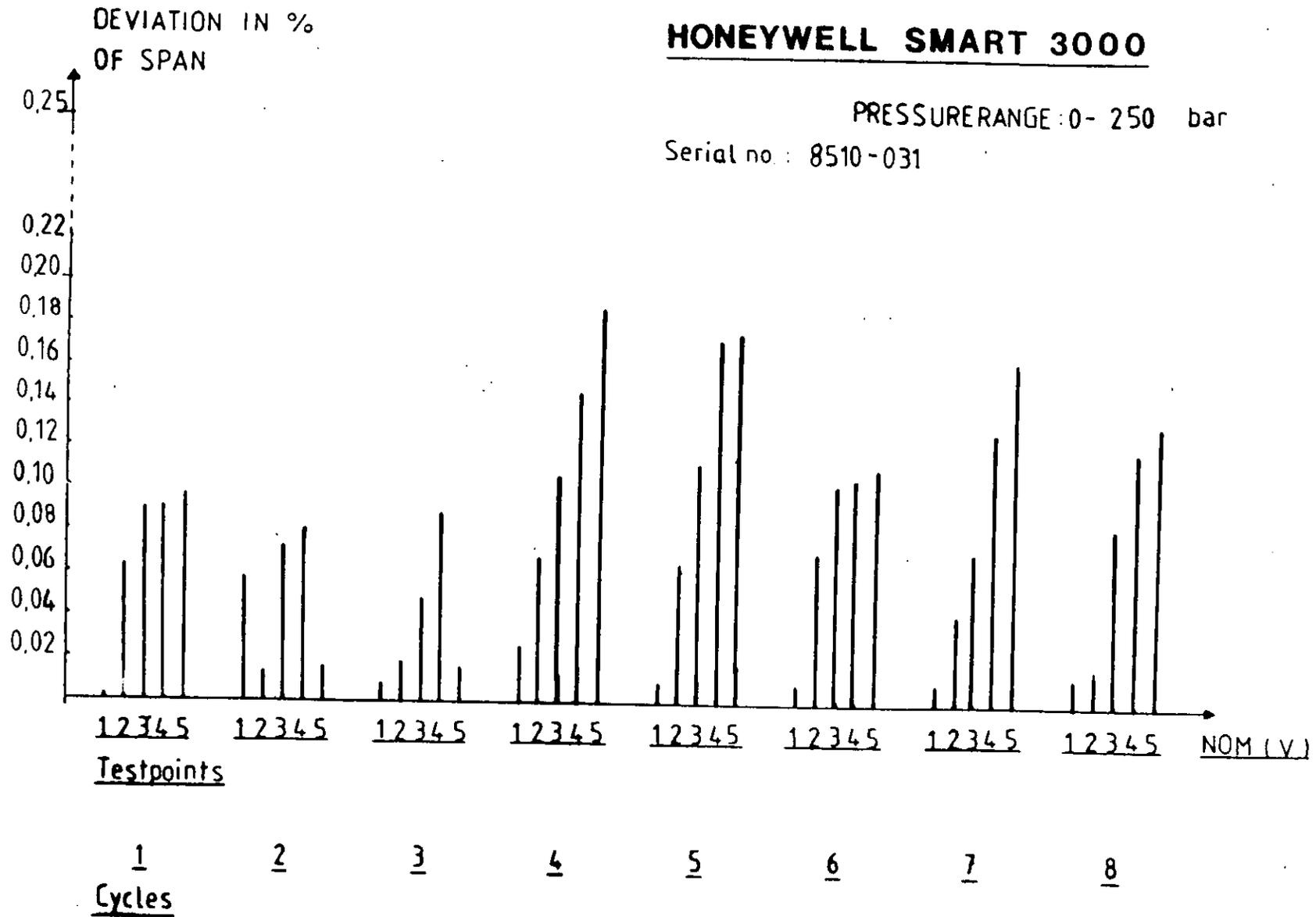


FIG 12

NORSKE SIVILINGENIØRERS FORENING

NORTH SEA FLOW METERING WORKSHOP

Stavanger Forum, Stavanger
13 - 15 oktober 1987

METERING MULTIPHASE WELL FLOW.
MEASUREMENT TASK AND POTENTIAL SOLUTIONS.

3.1

Foreleser:
B.I.Kalland
Statoil

Ettertrykk kun etter skriftlig tillatelse fra NIF og forfatteren.

METERING MULTIPHASE WELL FLOW.
MEASUREMENT TASK AND POTENTIAL SOLUTIONS.

1. Introduction

To make future marginal and deep-water field economically viable, development concepts based on subsea technology to a large extent are required. For advanced subsea production systems, where unprocessed or partially processed wellstreams are transported in pipelines from remote manifold centres at the well site to distant processing facilities on production platforms or on-shore, key critical equipment still remains to be qualified. Metering equipment for periodic well production testing located at a remote well site are one of those critical components not yet available, considered to have a high potential in such subsea field developments. This measurement problem definitely represents an extremely complex flow metering task, and a number of oil companies and manufacturers are presently running development projects on various more or less sophisticated concepts to possibly solve this problem.

2. The need

As a part of the well production testing programme for a producing field, periodic production testing is needed, i.e. at regular intervals determine gas, oil (condensate) and water production rates from individual wells under normal production conditions.

From an operational point of view this information in general is needed for the following purposes:

1. Reservoir management

Close reservoir monitoring for updating of reservoir models is needed to enable reliable prediction of future reservoir behaviour as a basis for planning of later optimal production strategy.

2. Operational supervision and control

Flow rate information is needed for well production rate optimization, detection of gas or water breakthrough, and monitoring of well condition, i.e. indicative information on equipment failure, perforation/gravel pack failure etc.

3. Production allocation

In case multiple wellstreams from different owners are commingled into common pipelines or separator trains, upstream well production testing data may provide the basis for production allocation.

To what extent well production rate information is needed in terms of flow parameters, accuracy and frequency for the above purposes is determined by highly field specific factors such as

- reservoir properties
- overall field development concept
- operational strategy

3. Present technology

Existing solutions to periodic production testing of wells being commingled into a single pipeline at a distance from a central processing facility include the following alternatives:

- Testline from subsea (or wellhead platform) manifold centre to test separator at processing facility.
- Riser from subsea installation to test separator on surface vessel.
- Well shut-down and measurement of corresponding change in wellhead pressure or in production separator output.

Between tests the wellhead pressure provides flow measurement data based on updated pressure-flow rate correlations, and additionally signals well problems.

In the latter case above excessive production testing after workover or on problem wells is supposed to be carried out from a surface vessel.

4. Potential of new technology

In general, the following factors will characterise field development concepts where direct well flow metering at the well site represents a possible technical-economical attractive alternative to the above conventional solutions:

- stringent production testing requirements with respect to accuracy and/or frequency
- long distance well site - processing facilities (typ. > 30 km)
- oil or low GOR gas/condensate reservoirs (typ. GOR < 5000)
- large number of wells (typ. > 4)

At unmanned wellhead platforms direct well flow metering equipment has a potential compared to conventional test separator designs in terms of reduced weight, volume, cost or maintenance needs.

Such equipment similarly will make an attractive alternative to test separator for allocation purposes at production platforms where production from new fields are brought into existing separator trains.

In short, well flow metering equipment may have an economical impact in the above field cases, through reduced investment and operating costs, and increased recovery by better reservoir management, and additionally allow for increased flexibility in phased field developments.

However, the actual potential of such equipment in a give field development to a large extent depends on highly field-specific factors, such as:

- * Type of reservoir
- * Field development concept
- * Operating philosophy

i.e. the field concept has to be developed to a sufficiently specified, conceptual level before assessment of the real potential of multiphase metering equipment can be done.

5. Measurement task

The actual measurement information needed is well production rates of gas, oil and water, i.e. flow rates averaged over a sufficiently long interval to be repre-

sentative for long term mean production rates. (For test separators: up to 24 hours).

The overall key equipment requirements are (guideline data):

Absolute accuracy	:	5% of measured value
	:	lower range: 2% FSD
Max. rates	:	30000 bbl/d
GOR	:	0 - 20
WOR	:	0 - 4
Measurement interval	:	1 - 2 months
Reliability	:	MTBF = 5 years
Unit lifetime	:	20 years

Key critical process condition, installation and maintenance requirements include (guideline data):

- * Design pressure : 300 bar
- * Temperature : 150 bar
- * Complex time-varying inlet flow patterns
- * Phase composition variation
- * Erosion
- * Corrosion
- * Scaling
- * Wax
- * Emulsion
- * Foaming
- * Wet system
- * Essentially no in-situ calibration options
- * Long maintenance intervals

Meeting the above combined measurement performance and reliability requirements under the conditions as indicated definitely represent an extremely complex flow measurement task.

6. Potential concept solutions

6.1 General characteristics

At an overall level realistic system concepts will functionally consist of two different parts: flow conditioning devices and a set of measurement instruments. Physically the two types of components will be more or less integrated.

A complete measurement system will be located in a test line within the field installation, coupled to individual wells via a test/kill manifold, see Fig. 1.

Flow conditioning devices

In practice, each of the potential attractive partial measurement systems in question will need a high degree of local flow conditioning to function satisfactory. Essentially, homogeneity and no slip conditions, or separated gas and liquid rate measurements are needed. Thus homogenization and/or separation devices are required, to be installed in the main test line and/or in a by-pass loop, see Fig. 2.

The practical problem relates to designing rugged and reliable equipment that can perform the conditioning function as required over a large span of mean production rates, and for worst case transient conditions.

Two- or three-phase test separators custom designed for the given conditions would represent the highest level of such a flow conditioning device.

Measurement instruments

Parallel measurements of a minimum set of flow parameters are needed to enable extraction of gas, oil and

water flow rates. In addition to standard pressure and temperature measurements, suitable combinations of partial measurement equipment for phase fractions and bulk velocity or volumetric/mass flow rates are required.

6.2 Partial measurement methods

The partial measurement methods considered to have a potential in multiphase flow metering systems are essentially modified versions of commercially available equipment widely used in single and two-phase flow in industrial applications.

The problem of adapting these systems to our application in general relates to the following limiting factors:

Accuracy:

- time response
- measurement range
- sensitivity to deviation from ideal local flow condition
- phase composition sensitivity
- pressure and temperature sensitivity

Long term stability:

- sensor/interface electronics stability
- erosion/corrosion/scaling sensitivity

Reliability:

- sensor/electronics complexity
- resistance to hostile conditions

Unit lifetime:

- lifetime of hardware components
- resistance to inner/outer environment.

To meet the accuracy and reliability requirements auto-calibration, self-checking functions and redundancy systems must be built-in at different system levels.

Beneath are listed the partial measurement methods considered to be most attractive. The methods listed appear in different versions in system concepts developed by oil companies, manufacturers and institutions.

Water fraction	:	capacitance microwave low energy gamma neutron-based method
Gas fraction	:	gamma densitometry impedance neutron-based method
Bulk velocity	:	acoustic cross-correlation pulsed neutron activation
Mass/volumetric flow rate	:	coriolis diff. pressure (orifice, venturi) turbine acceleration force

Assessing the feasibility of any partial measurement method has to be done against a sufficiently defined total system concept, i.e. the complementary measurement methods and flow conditioning devices to be applied must be specified.

7.. Examples of complete measurement systems

In fig. 3 and 4 two measurement systems are given that have both reached a high level of development. The systems are developed by Texaco USA at Texaco's Houston Research Center and by Euromatic Machine & Oil Company Ltd, UK respectively. The system block descriptions serve to illustrate the overall system complexity that is considered needed to practically solve the multiphase well flow metering task.

8. Conclusion

After intensive parallel R&D-work during the latest 5-7 years among oil companies, manufacturers and R&D-institutions direct multiphase well flow metering equipment is still not qualified for field applications.

However, the potential impact of such equipment on future marginal and deepwater field economy will remain a driving force for continuing development work in this area.

The level of development currently reached for different concepts being recently launched certainly indicates that this metering task will be solved for specific field applications within the next 3-5 years.

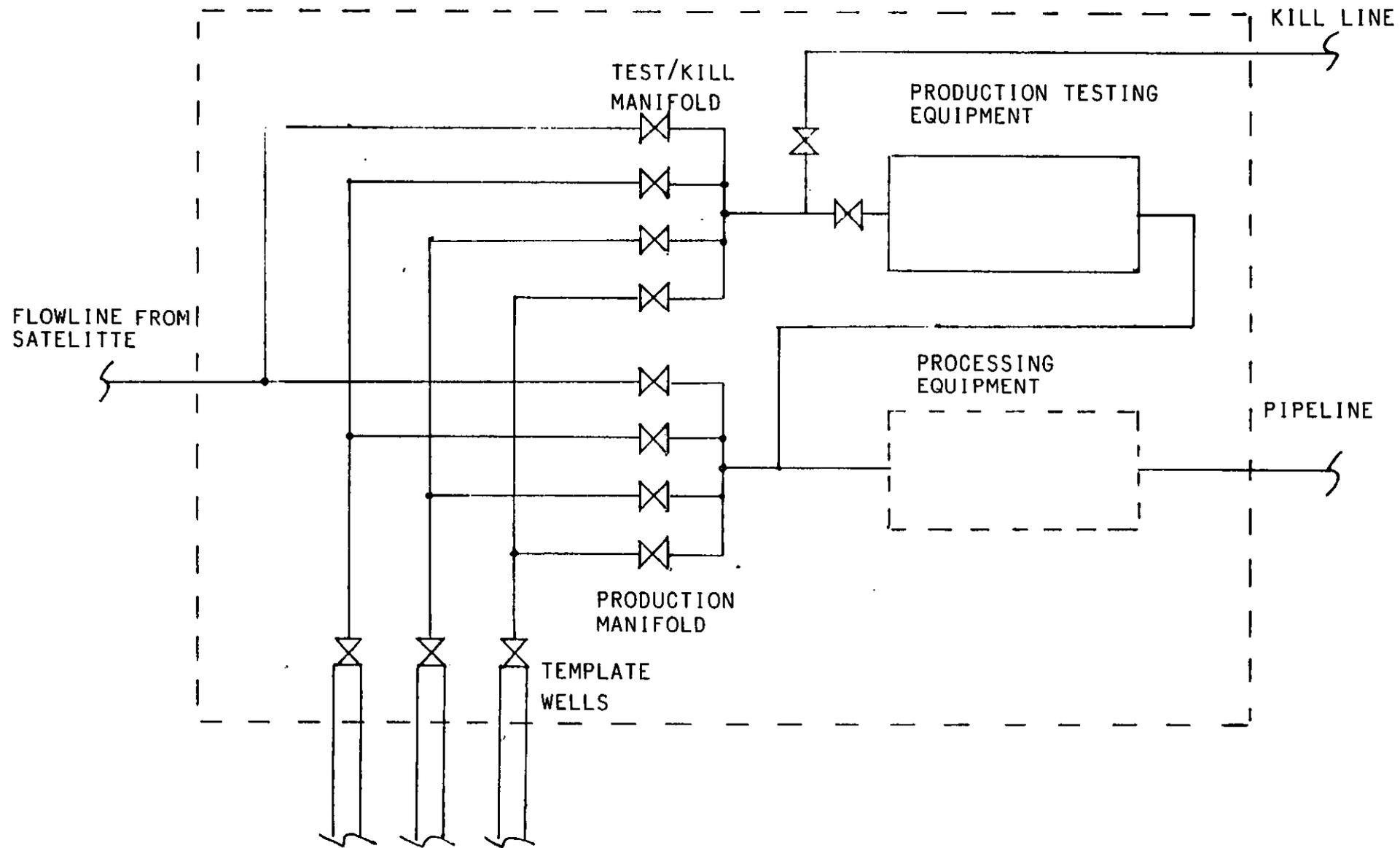
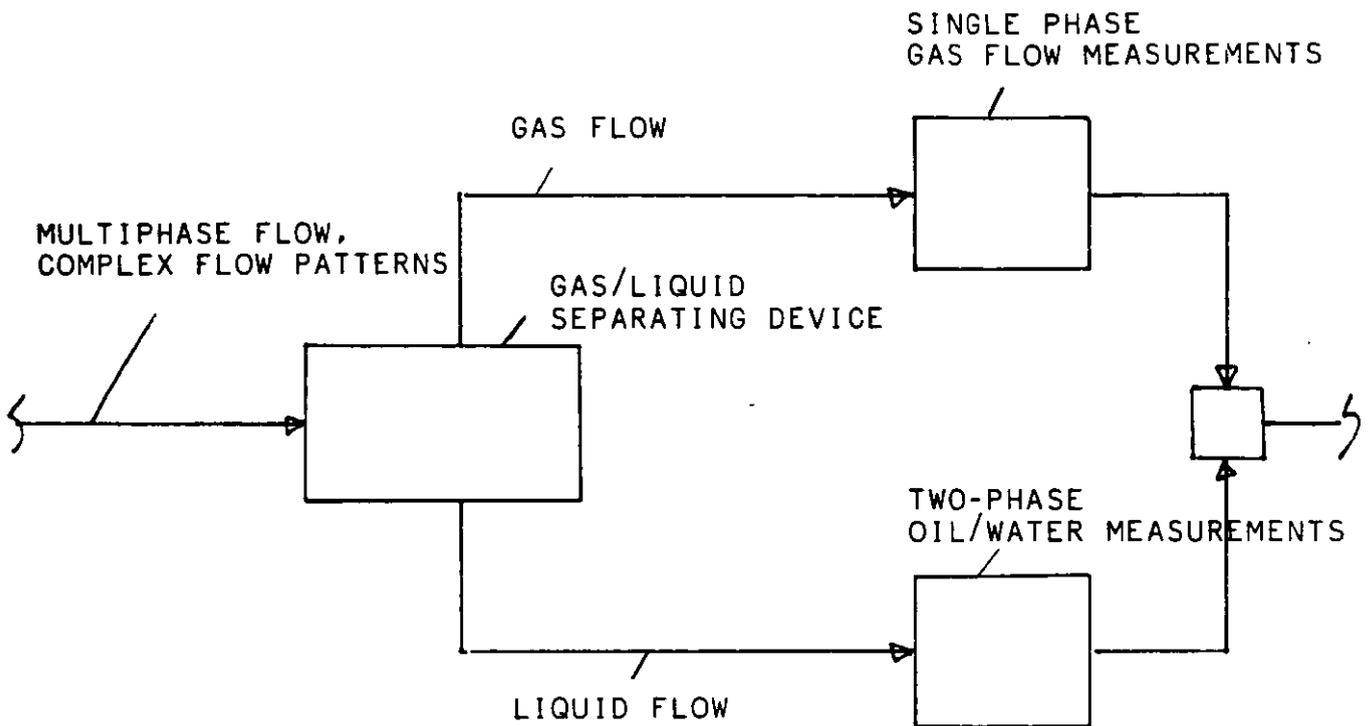


FIG. 1 LOCATION OF PRODUCTION TESTING EQUIPMENT
WITHIN SUBSEA STATION

SEPARATION:



HOMOGENIZATION:

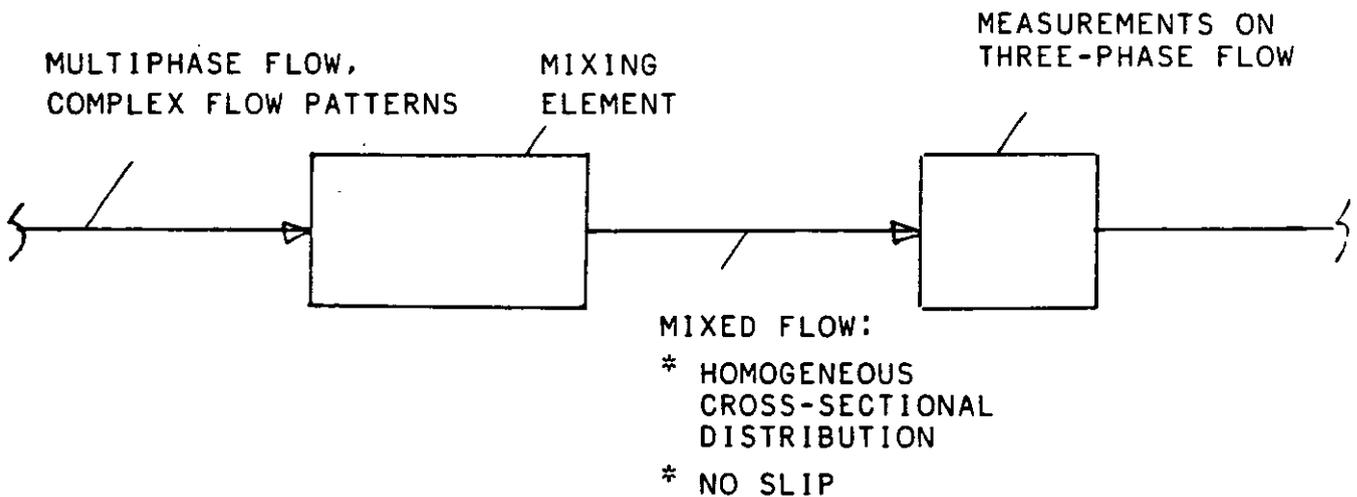
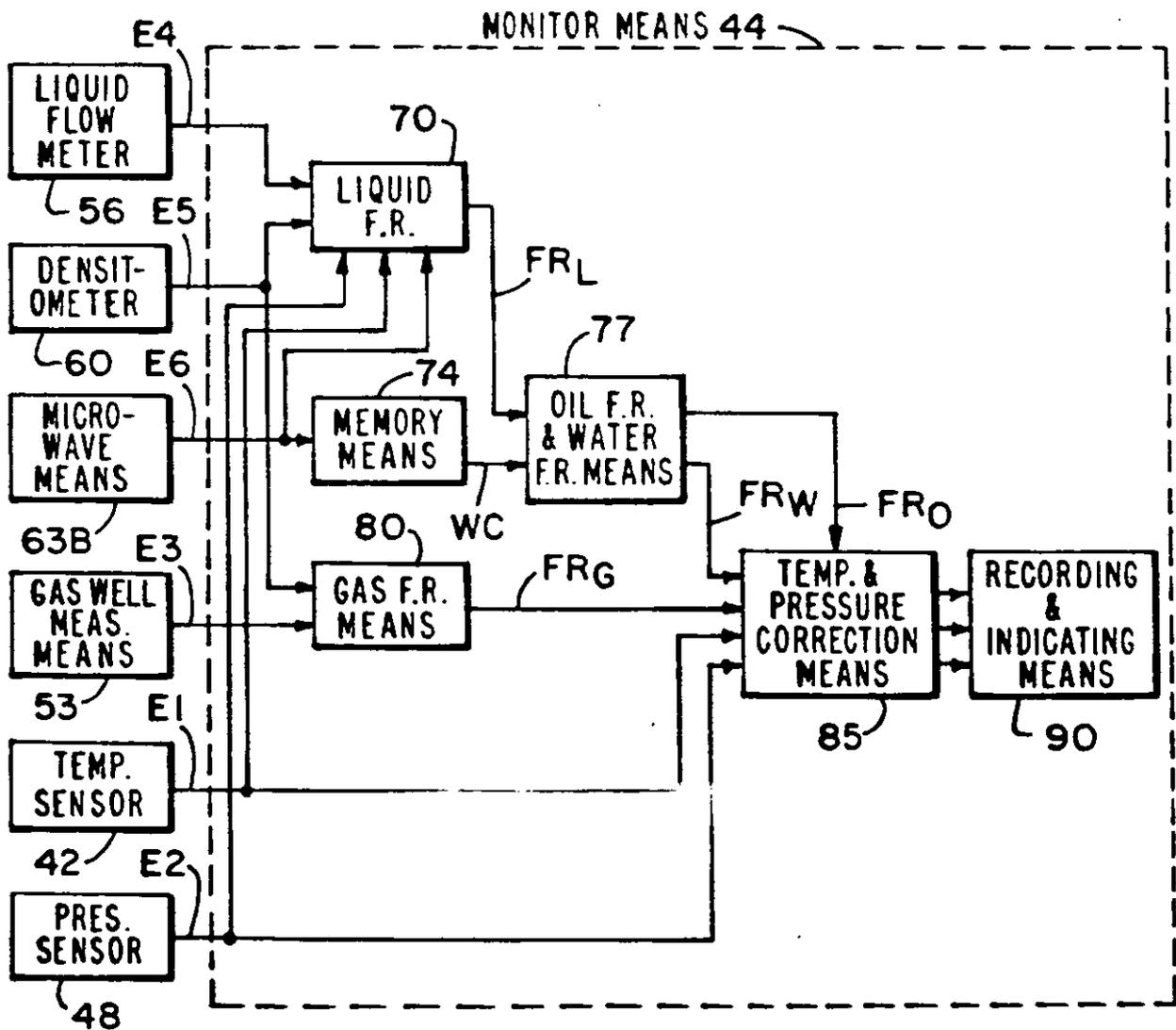
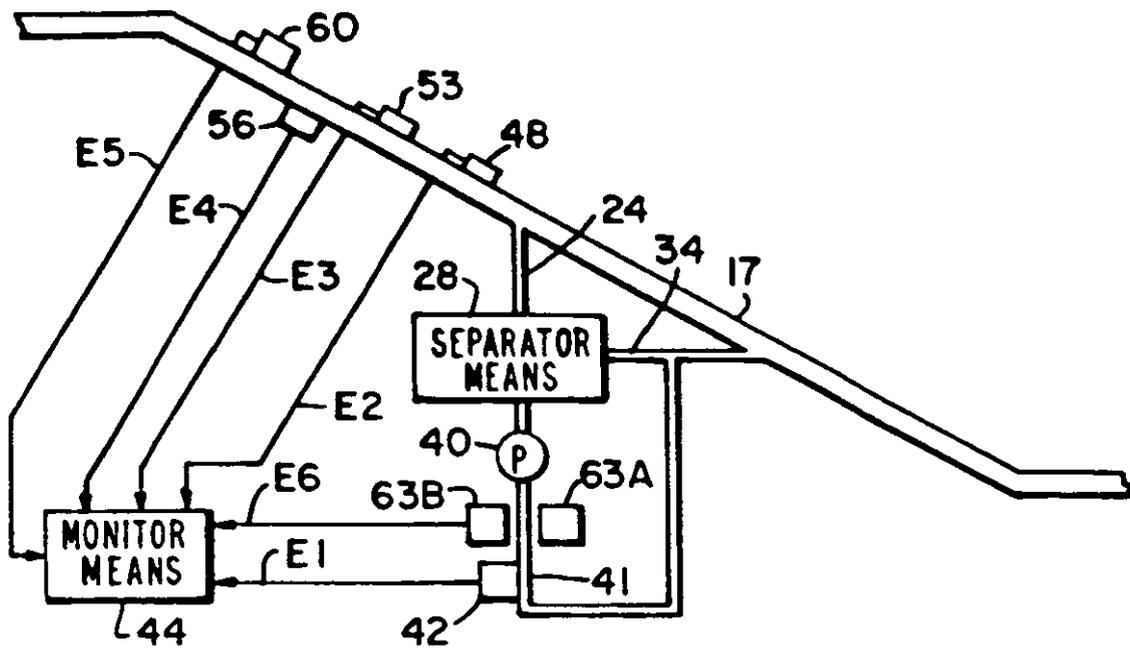


FIG. 2 FLOW CONDITIONING ELEMENTS LOCATED IN MAIN TEST LINE OR BY-PASS LOOP.



COPY FROM US PATENT NO. 775073

FIG. 3 WELL FLOW METERING SYSTEM DEVELOPED BY
TEXACO, HOUSTON RESEARCH CENTER, USA

DIAGRAMMATIC REPRESENTATION
 THE 3 PHASE
 FLOWMETERING SYSTEM.

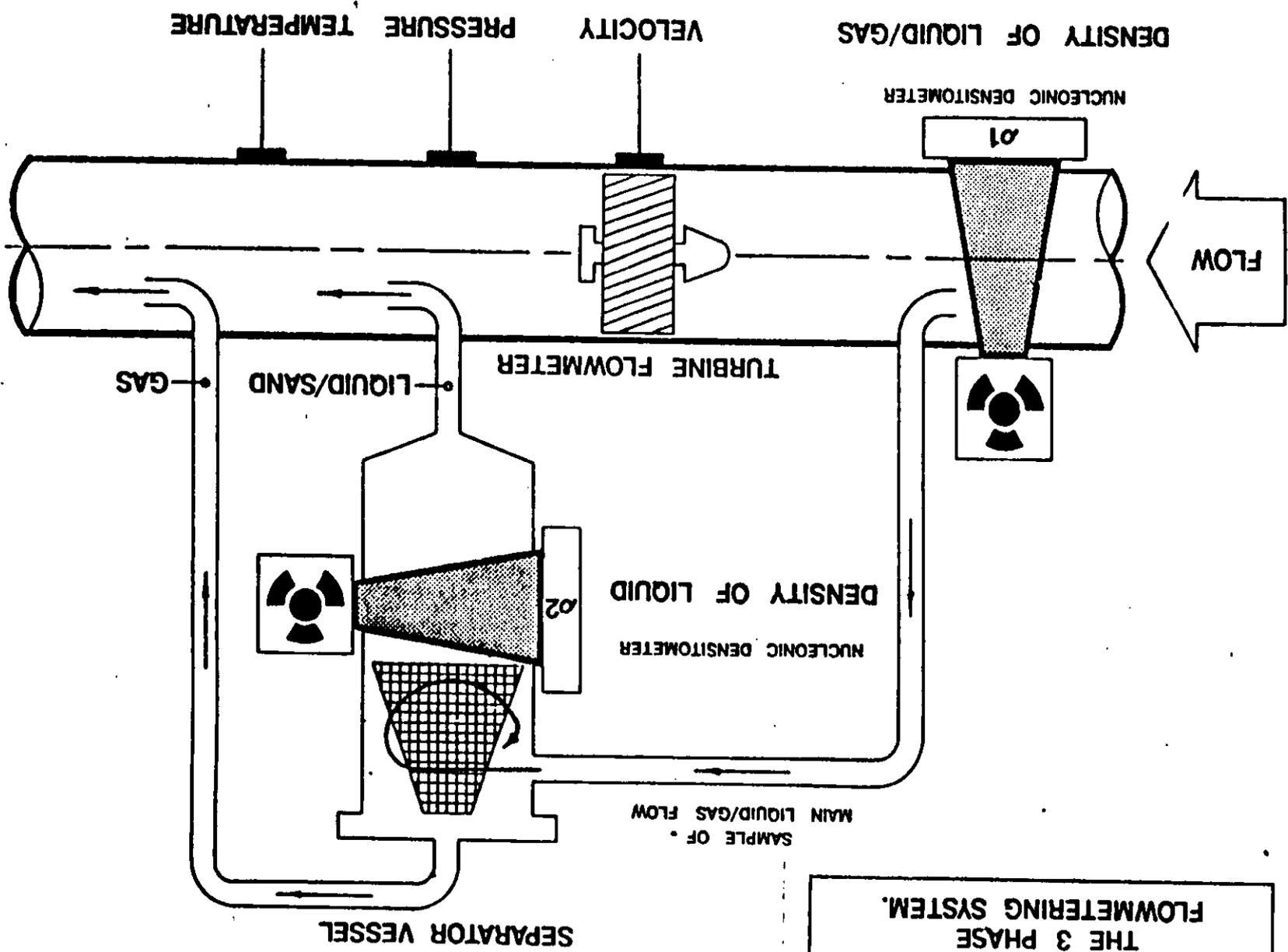


FIG. 4 WELL FLOW METERING SYSTEM DEVELOPED BY
 EUROMATIC MACHINE & OIL COMPANY LTD., UK

NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

Main Index

**NORTH SEA FLOW METERING
WORKSHOP**

13 - 15 October 1987

Stavanger Forum, Stavanger

THE EFFECTS OF LIQUIDS ON ORIFICE PLATES
METERING GAS

3.2

Lecturer: Scientific Officer
A. Moore, NEL

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DEPARTMENT OF TRADE AND INDUSTRY
NATIONAL ENGINEERING LABORATORY

THE EFFECTS OF LIQUIDS ON ORIFICE PLATES METERING GAS

by

A Moore
(Flow Measurement and Turbomachinery Division)

S U M M A R Y

The influence of relatively small amounts (say up to 5 per cent by mass) of liquid contamination when metering natural gas with orifice plates are examined. It is shown that all the established correlations predict substantially the same minor, but significant, effect.

An approach to correcting (for known gas quality) mass flowrates, determined using the established equations based upon the meter performance with dry gas, is suggested.

The influence of mixture quality has been discussed and some suggestions for the on-line measurement of 'gas quality' are given.

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NOTATION

A	Area of flow	m^2
A_2	Area of orifice throat	m^2
C_d	Discharge coefficient	-
C^*	Relative capacitance	-
D	Diameter of pipe	m
d	Diameter of orifice bore	m
Fr_m^2	Modified Froude number (defined in equation (2))	-
f(1)	Function defined in equation (12)	-
f(2)	f(1) modified by the inclusion of 0 for constant 1.26	-
g	Gravitational acceleration	m/s^2
h	Height above the datum level	m
K	Mean velocity ratio (U_G/U_L)	-
P	Pressure	Pa
ΔP	Differential pressure at orifice	Pa
Q_m	Mass flowrate of fluid in single-phase flow	kg/s
U	Mean velocity (applicable to two-phase flow)	m/s
W	Mass flow of mixture	kg/s
W_C	Mass flow of condensate	kg/s
W_G	Mass flow of gas in two-phase flow	kg/s
W_G^*	Inferred mass flow of gas	kg/s
W_{HC}	Total mass flow of hydrocarbons	kg/s
W_L	Mass flow of liquid in two-phase flow	kg/s
W_W	Mass flow of water	kg/s
X	Lockhart-Martinelli parameter	-
x	Quality (mass dryness fraction) W_G/W	-
y	Liquid ⁰ fraction (= $1 - x$)	-
z	Water cut ($z = W_W/W_L$)	-
β	Orifice plate diameter ratio	-
e	Expansibility factor (applied to flow through an orifice)	-

θ	Correction factor (function of density ratio)	-
ρ	Density	kg/m ³
Φ	Two-phase multiplier	-
Ω	Void fraction (= A_G/A)	-

Subscripts

1	Refers to conditions at station upstream of orifice
2	Refers to conditions at the throat measuring position
G	Value of variable for gas
L	Value of variable for liquid
s	Superficial value
t	Value in two-phase flow

1 INTRODUCTION

This paper addresses itself to the potential errors that can be introduced into a measurement of a gas flowrate through an orifice plate by the presence of a small quantity of liquid. This may, in the case of a system distributing natural gas, be condensate or water, or more probably a mixture of both. Our work is at present mainly concerned with systems metering natural gas, since the commercial implications of even quite small errors can be very significant. This allows one to arbitrarily impose limitations on the general topic of two-phase flow through orifice plates and directed my approach to the existing literature, which in general, is quite extensive. Initially the liquid phase was seen as a contaminant and was not treated as a useful commodity. This suggested that the most sensible approach would be to concentrate on the study of work which has used the gas phase as the basis for the correlation between a single-phase measurement and that in the two-phase environment.

It is not intended that this paper shall be a definitive study of the problem, but it is seen rather as a vehicle which may stimulate this forum in a discussion of the current state of the art and help in the identification of those areas into which future investigations might most usefully be directed.

2 STATEMENT OF THE PROBLEM

In the metering of natural gas it is recognised that in order to get an 'accurate' measure of the quantity it is necessary to separate the gas from any associated liquids. Plant to accomplish this is invariably included in any distribution/metering system. It has been suggested that condensate can, even with such plant fitted, be present as a contaminant in metering stations. Additionally operators, faced with the need to apportion - using orifice plates - the flow of mixture from a number of sources, are seeking improved accuracy. The case where a high quality two-phase mixture, rather than pure gas, passes through the meter, has been studied.

The problem is therefore stated: if one infers the gas mass flowrate, based on measurement of pressure difference across the orifice plate (Fig. 1) as W_G^* , where,

$$W_G^* = \frac{C_d \epsilon A_2}{\sqrt{1 - \beta^*}} \sqrt{2\Delta P \rho_G} \quad \text{kg/s} \quad (1)$$

what are the likely errors associated with such an estimate for the mass flowrate of gas given that the pressure difference ΔP is due to the passage of a mixture of gas and condensate? It may also be expressed; what level of liquid contamination can be allowed in gas metering systems before one can expect to find significant errors in the assessment of gas mass flowrate through the orifice plate?

In this treatment it has been envisaged that liquid contamination could be as high as 5 per cent by mass.

3 TWO-PHASE FLOW IN PIPES AND THROUGH ORIFICE PLATES

Simultaneous flow of gas and liquid through pipes features a variety of regimes which have been described, typically^{1, 2}. Attempts have been made to develop maps which encompass most of the variables and typical of these are

the two shown in Figs 2a and 2b, which are derived by Dukler and Taitel³. More recently the phenomena of liquid accumulation upstream of orifice plates has been reported by both Norman et al⁴ and in the work⁵ carried out under Dr Boe's direction here in Norway at the Rogaland Research Institute. The build up of liquid upstream of the plate influences the pressure difference measured at the plate in a manner rather different to that caused by the two-phase flow through the plate and discussed in some detail in paragraph 4 of this paper. It has been shown⁵ that liquid accumulation leads to an under-estimation of gas mass flow, while the effect of the liquid passing through the plate leads to an over-estimation of the gas mass flow.

3.1 Liquid Accumulation: When Is It Significant?

The liquid accumulation effect has been reported in work carried out at ambient pressure or relatively moderate air pressures. It has been shown⁵ that the build up of liquid in front of the plate can be correlated against modified Froude No Fr_m , ie a Froude number based upon the superficial gas velocity and modified by the density ratio,

ie,
$$Fr_m^2 = \frac{\rho_G/\rho_L}{1 - \rho_G - \rho_L} \frac{(U_{GG})^2}{gD} \quad (2)$$

Examination of the data given in Reference 5 suggests that the effect of liquid accumulation is negligible when the value of Fr_m^2 exceeds 0.15. We have therefore explored the behaviour of equation (2) for a range of density ratios, pipe sizes and superficial gas velocities. A threshold value (when $Fr_m^2 = 0.15$) for superficial gas velocity above which the effect of liquid accumulation is negligible has been calculated for a range of gas/liquid density ratios and is shown plotted in Fig. 3.

One observes from this analysis that it is most unlikely, since the velocities and densities encountered will be high, in practical natural gas metering installations, that one will find liquid accumulating upstream of the orifice plate.

Consequently, in this paper, no further reference is made to the phenomenon.

4 PUBLISHED DATA: MEASUREMENTS OF PRESSURE DIFFERENCE AT THE PLATE IN TWO-PHASE FLOW THROUGH ORIFICE PLATES AND DERIVED CORRELATIONS

A great deal of work has been carried out in this field over the years and much of it has resulted in 'a new correlation'. Surprisingly little of this work has, however, been addressed directly to the problem with which we are concerned although, as it transpires, most of it has some relevance.

4.1 Pressure Difference Measurements and Correlations

In a 1962 paper⁶ Murdock presented data which is directly relevant. This was derived from tests carried out by W H Osborne of the Champlin Oil and Refining Company. He had conducted laboratory and field tests on a variety of mixtures, including gas/distillate and gas/water combinations at representative (920 lbf/in²) gas pressures. Data derived from the flow of steam/water mixtures through orifice plates measured in the Naval Boiler and Turbine Laboratory were also used by Murdock in the development of his correlation. He employed the two-phase multiplier

$$\Phi_G^2 = \frac{\Delta P_t}{\Delta P_G} \quad (3)$$

and found a linear relationship (reproduced in Fig. 4) between it and the Lockhart-Martinelli' parameter X. The best fit line to the data is given by

$$\Phi_G = 1 + 1.26X \quad (4)$$

with the corresponding expression for the mass flow of the mixture as

$$W = \frac{C_{dG} A_2 \epsilon_G}{\sqrt{(1 - \beta^*) x + 1.26(1 - x) \epsilon_G (C_{dG}/C_{dL}) \sqrt{(\rho_{G1}/\rho_{L1})}}} \sqrt{(2\Delta P_t \rho_{G1})} \quad (5)$$

where x, the quality of the mixture is defined

$$x = W_G/W = 1 - y$$

where y is the liquid fraction and

$$y = W_L/W.$$

The Osborne tests were carried out in reasonably sized pipework, up to 100 mm diameter, with representative plate beta ratios, as detailed in the table in Fig. 4.

Typical of the other data sources is the work^{8, 9} carried out by Chisholm and his co-workers at the UK National Engineering Laboratory where measurements were made with steam/water mixtures in quite small (50 mm) diameter pipework. A correlation between the two-phase multiplier and the Lockhart-Martinelli parameter

$$\Phi_G^2 = 1 + 2.66X + X^2 \quad (6)$$

was developed as a result of this work. For high quality flows there is, as shown in Fig. 5, little difference between the results given by the Murdock and Chisholm correlations, for quite wide ranging differences in measurement conditions.

This general approach has been widely followed and more recent work with steam/water and Freon-113 has extended the data to higher ($\rho_G/\rho_L \leq 0.33$) density ratios. In place of the single equation (4) Lin¹⁰ found that the parameter Φ_G varied with the density ratio ρ_G/ρ_L and derived the empirical relationship between his correction factor θ and density ratio shown plotted in Fig. 6. Where his factor θ is given in

$$\Phi_G = 1 + \theta X. \quad (7)$$

He showed that the distinction between the liquid and vapour phases tends to reduce as the pressure increases. The mixture behaviour clearly approaches that of an homogenous fluid and the value of θ tends to unity as the density ratio is increased.

Lin preferred to use the liquid density as the basis for his correlation, claiming that it gave better results when vapour quality x was greater than 0.1. The preferred correlation due to Lin is

$$W = \frac{C_{dL} A_2}{\sqrt{(1 - \beta^*) \{ (1 - x)\theta + x\sqrt{(\rho_L/\rho_G)} \}}} \sqrt{(2\Delta P_t \rho_L)} \quad \text{kg/s.} \quad (8)$$

The discharge coefficient is that appropriate to the orifice with liquid flow alone and in the tests referred to it was measured using liquid Freon. The test line was horizontally mounted and 32 mm diameter. A range of orifice diameters were tested, giving diameter ratios β of 0.311, 0.439 and 0.624 respectively. Density ratios of 0.1425, 0.2150, 0.2450 and 0.3280 were used and the highest pressure reached 0.832 of the critical value. Qualities were determined from heat flux measurements and estimated to be accurate to within ± 1.0 per cent.

Teigen and his co-workers¹¹ reached slightly different conclusions from their measurements in high pressure (69-200 bar) steam/water mixtures. They found that their results were best correlated by the simple 'no slip separated flow' model, ie the correction coefficient θ takes the value unity.

4.2 Comparison Between Inferred and True Gas Flowrate

The inferred mass flowrate W_G^* is derived using equation (1). The actual mass flow of the two-phase mixture W may be estimated, if the mixture quality is known, using the expression⁵ due to Murdock. This may be expressed in terms of the inferred gas flowrate

$$\text{ie, } W = \frac{W_G^*}{1 + y(1.26 \frac{C_{dG} \sqrt{(\rho_{G1})}}{C_{dL} \sqrt{(\rho_{L1})}} - 1)} \quad \text{kg/s} \quad (9)$$

Combining equation (9) with the expression for the liquid fraction y , one obtains

$$\frac{W_G}{W} = \frac{W_G^*}{W} \frac{1}{1 + y \left\{ 1.26 e \frac{C_{dG} \sqrt{(\rho_{G1})}}{C_{dL} \sqrt{(\rho_{L1})}} - 1 \right\}} - y \quad (10)$$

$$= 1 - y.$$

The ratio - $\frac{\text{true mass flowrate of gas}}{\text{inferred gas flowrate}} = \frac{W_G}{W_G^*}$

may be written in the form

$$\frac{W_G}{W_G^*} = \frac{1 - y}{(1 - f(1)y)} \quad (11)$$

$$\text{where the function } f(1) = 1 - 1.26 e \frac{C_{dG} \sqrt{(\rho_{G1})}}{C_{dL} \sqrt{(\rho_{L1})}} \quad (12)$$

varies with both gas and liquid Reynolds' numbers and hence with change in quality. The dependence is relatively weak, hence it is meaningful to explore the behaviour of equation (11) with $f(1)$ maintained constant. The assessment is based on the conditions cited in Murdock's paper⁵, ie natural gas at 62 bar and with both water and distillate as contaminants.

These relations may be made more generally valid by substituting θ for the constant 1.26 in equations (10) and (12) and using values for θ appropriate to the mixture density ratio.

Contamination has its greatest influence on equation (11) when the density ratio ρ_G/ρ_L is a maximum. The value of $f(1)$ when the mixture is comprised of gas and distillate at a pressure of 62 bar is typically

$$\begin{aligned} f(1) &= 1 - 1.26 \times 0.992 \times (0.603/0.66) \times f(50.18)/f(758) \\ &= 0.706. \end{aligned}$$

The ratio (for natural gas) of true flowrate/inferred flowrate has been plotted in Fig. 7. Also shown in this figure are corresponding ratios derived for two models, viz. air/water at ambient pressure and air/oil at 8 bar; both of which could be fairly readily studied in the laboratory. The input data used in their derivation is summarised in Table 1.

It is evident that at practical density ratios a limited amount of liquid contamination may be allowed before one needs to take account of its direct effect on the orifice plate readings. It is also evident that one should beware of drawing conclusions about the accurate measurement of flowrate in natural gas two-phase mixtures based upon results measured in the laboratory with quite unrealistic mixture density ratios.

4.3 Allocation and the Effect of Another Liquid Component

In the discussion so far the liquid has been seen as a contaminant, however in most cases the liquid passing through the meter is either recovered or evaporated downstream. Then it is assumed that the mass flow of the mixture is of primary interest. The mass flow of the mixture can be related to the inferred flowrate of the gas using

$$\frac{W_G^*}{W} = 1 - f(2)y \quad (13)$$

where the coefficient $f(2)$ (ie the more general form of $f(1)$ with θ used in place of Murdock's constant) has now been adopted. The ratio mixture mass flow to inferred mass flow of gas W/W_G^* has been plotted against liquid fraction in Fig. 8a for the case of natural gas at 200 bar. The case where the gas is at 62 bar has been plotted in Fig. 8b.

It is significant and obvious that the correction is now in the opposite sense. The mass flowrate of hydrocarbons, which is the commodity of interest, has been under-registered by taking an inferred value for the mass flowrate of gas.

The mixture which is passed through an orifice plate downstream of a wellhead separator is comprised of at least three components, wet, gas, water and condensate. If we assume that the commercial values (by mass) of the condensate and gas are equal and take that of the water as zero then we will have a mixture of hydrocarbons, the mass flowrate (W_{HC}) of which is the commodity which we wish to know or allocate.

Writing,

$$W_L = W_W + W_C$$

and defining a water 'cut' as $z = W_W/W_L$, then the mass W of gas/liquid mixture passing through the orifice plate is now given by

$$W = (W_W + W_C) + W_G$$

and the valuable commodity, the mass of hydrocarbons W_{HC} is given by

$$W_{HC} = W_G + W_C.$$

Using the relations for W_G/W_G^* and W/W_G^* previously determined one arrives at an expression for the valuable hydrocarbon mixture

$$\frac{W_{HC}}{W_G^*} = \frac{1 - zy}{(1 - f(2)y)}. \quad (14)$$

The ratio W_{HC}/W_G^* takes the value 1 if the water 'cut' $z = f(2)$. In this case no correction to the value given by the inferred gas flowrate need be made. This condition varies with pressure and vapour composition, ie density ratio. The ratio W_{HC}/W_G^* has been plotted against liquid fraction y for a range of water 'cuts' z in Figs 9a and 9b. With natural gas at 200 bar the zero correction water 'cut' is between 50 and 60 per cent. In the case of natural gas at 62 bar it is nearer 80 per cent.

It must be stressed at this stage that the analysis is approximate and that the plotted characteristics will have to be modified to take account of the variation in the parameter $f(2)$ with density ratio and the variation in density of the liquid fraction with water 'cut'. The analysis does however give a good indication of the scale of any correction needed.

5 MIXTURE PROPERTIES

In the treatment so far two fundamental issues have been avoided.

a A correction to the gas mass flowrate, inferred from the measurement of pressure difference at the plate, can only be made if the mixture quality x is known.

b The inferred flowrate can only be arrived at if the mixture density is known, or if the gas density can be determined from a knowledge of its equation of state.

Rather than attempt to offer specific solutions, a few notes on each topic shall be put forward for discussion

5.1 Sampling for Mixture Quality

In many cases the mixture quality will remain relatively stable for long periods of time. In such circumstances it is feasible for information on the liquid mixture and the gas properties to be determined by analysis of samples collected on a regular basis. These data taken with measurements of pressure and temperature at the meter will allow, with the aid of an equation of state, an estimate of component densities. One will then be in a position to correct an inferred gas flowrate, using the relations given above. The question that remains to be answered is - how well founded is one's knowledge of the equation of state?

5.2 On-line Determination of Quality

The continuous measurement of electrical capacity can be used¹² to provide a measurement of void fraction. In order to calibrate such an instrument the dielectric properties of the liquid mixture and the gas need to be known and remain sensibly stable with time. This approach will not be practical in three component flows, ie when the liquid phase is a mixture of condensate and water. Measurement of capacitance is feasible when it is clearly two-phase flow and is currently being employed¹³ in the North Sea for assessing water content in oil streams.

The use of this method at the high quality end of the gas/liquid two-phase flow spectrum appears to be eminently feasible. Fig. 10, reproduced from the static model experiments described¹⁴, shows that capacitance change is relatively sensitive to change in void fraction Ω in this flow regime.

The quality of the mixture is then inferred from a relationship of the type

$$1/\Omega = 1 + K \frac{\rho_G}{\rho_L} \frac{1-x}{x} \quad (15)$$

where $K = U_G/U_L$, the mean velocity ratio, is a function of the flow pattern and geometry of the capacitance meter. It will be noted that the density ratio is included in this expression.

It must be said that, while such an approach offers a sound basis for determining quality in association with an orifice plate, the combination will require considerable development before being useable as a reliable two-phase flow meter.

5.3 Simultaneous Determination of Quality and Mixture Flowrate

Wong, Rhodes and Scott¹⁵ showed that simultaneous measurement of frictional pressure drop and that due to momentum change in an accelerating flow could be correlated to yield mass flowrate in two-phase flow. They used a section of pipework with a twisted tape swirl generator for the frictional loss section and a Venturi meter downstream for the accelerating flow element. Fig. 11 (a and b) are reproduced from their paper and clearly show how the two distinct correlations intersect to yield a solution for each component of the mixture.

With high pressure two-phase flow of natural gas mixtures the frictional pressure drop in the pipe lines is measurable¹⁶ over quite short lengths. Such measurements taken with the pressure drop at the orifice plate will allow the derivation of liquid and gas flowrates. This approach would allow one to validate the technique for correcting inferred gas flowrate with a minimum of development, since the frictional pressure loss correlations¹⁶ are relatively well founded.

If one were to associate such instrumentation with an on-line flow computer then one has in prospect a 'smart orifice plate', with the ability to correct for liquid contamination.

6 IN CONCLUSION

The influence of relatively small amounts (say up to 5 per cent by mass) of liquid contamination when metering natural gas with orifice plates has been

examined. It has been shown that all the established correlations predict substantially the same minor, but significant, effect. Considering the effect of the liquid contamination as an error at the meter, then the actual gas flow will be about 1.5 per cent less than the value registered, with 5 per cent of the total mass flow present as liquid. Alternatively if the whole mixture is deemed to be commercially valuable then the meter will under register the total flowrate of hydrocarbons by about 3.5 per cent, under the same conditions.

An approach to correcting (for known gas quality) mass flowrate determined using the established equations based upon the meter performance with dry gas, has been suggested.

The influence of mixture quality has been discussed and some suggestions for the on-line measurement of 'gas-quality' have been presented.

ACKNOWLEDGEMENT

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LIST OF TABLES

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LIST OF FIGURES

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- 2b Flow regime map for air/water (ambient pressure)³
- 3 Threshold: liquid accumulation (gas/liquid density ratio 0.001-0.35)
- 4 Correlation of Murdock's⁶ data
- 5 Two-phase multiplier variation (cf Murdock, Chisholm & Lin at 62 bar)
- 6 Two-phase orifice plate correlations (cf Lin's correlation with Murdock and Teigen)
- 7 Two-phase actual gas flowrate (full-scale compared with two models)

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- 11 (a and b) Two typical W_L v. W_G plots from combination (twisted tape with Venturi meter¹⁵)

T A B L E 1

INPUT DATA FOR THE EXAMPLES CITED IN FIGS 5 AND 7

Mixture	Gas/distillate	Air/water	Air/oil
Pressure bar	62	1.0	8.0
Temperature °C	99	16	90
Gas density kg/m ³	50.18	1.20	7.64
Liquid density kg/m ³	758	1000	760
(density ratio) ^{1/2}	0.257	0.035	0.100
Function $\frac{C_{dG}}{C_{dL}} \epsilon_G$	0.907	0.980	0.900
Function f(1)	0.706	0.957	0.886

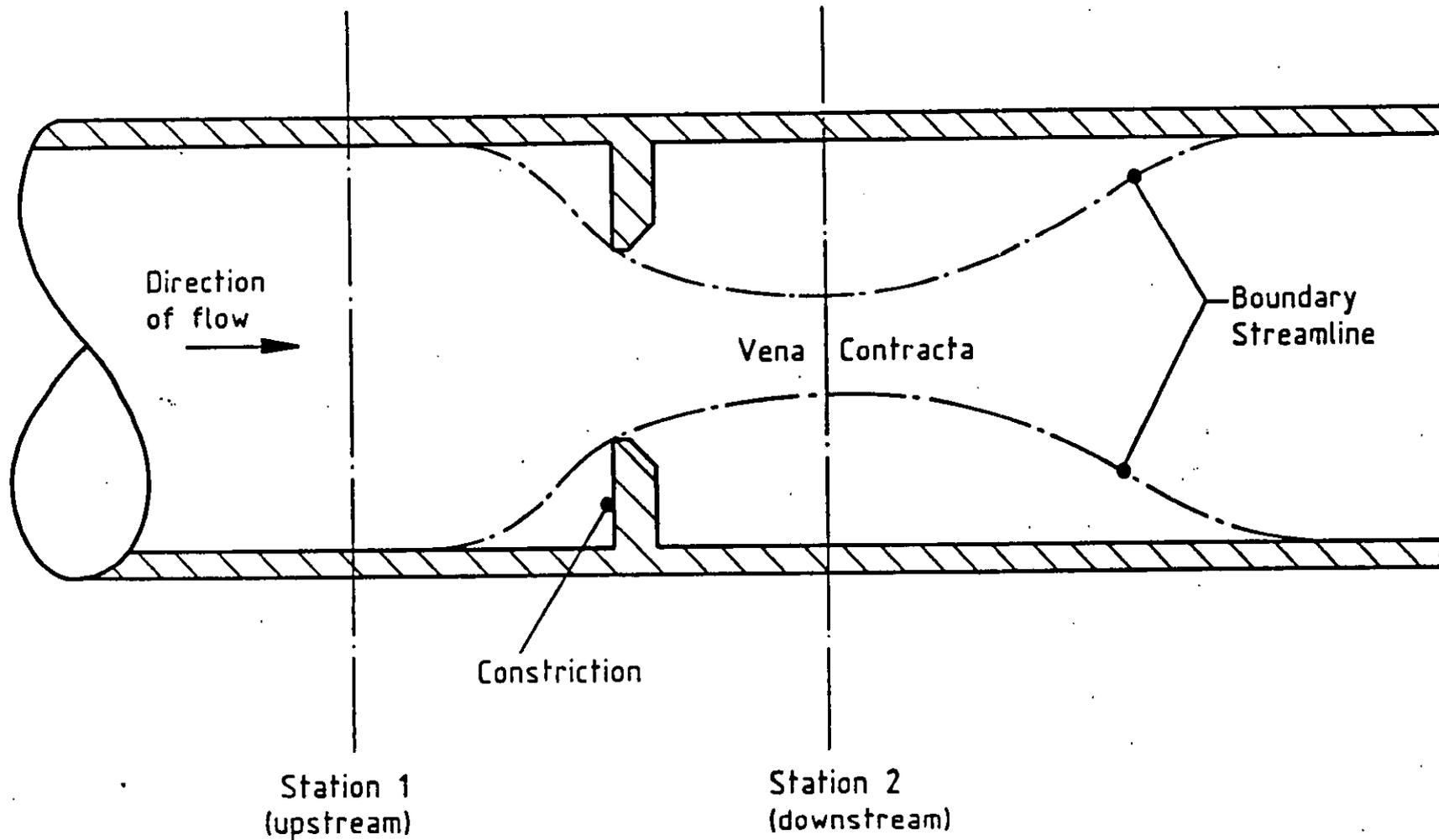


Fig 1 One Dimensional Flow Through a Pipe with a Constriction

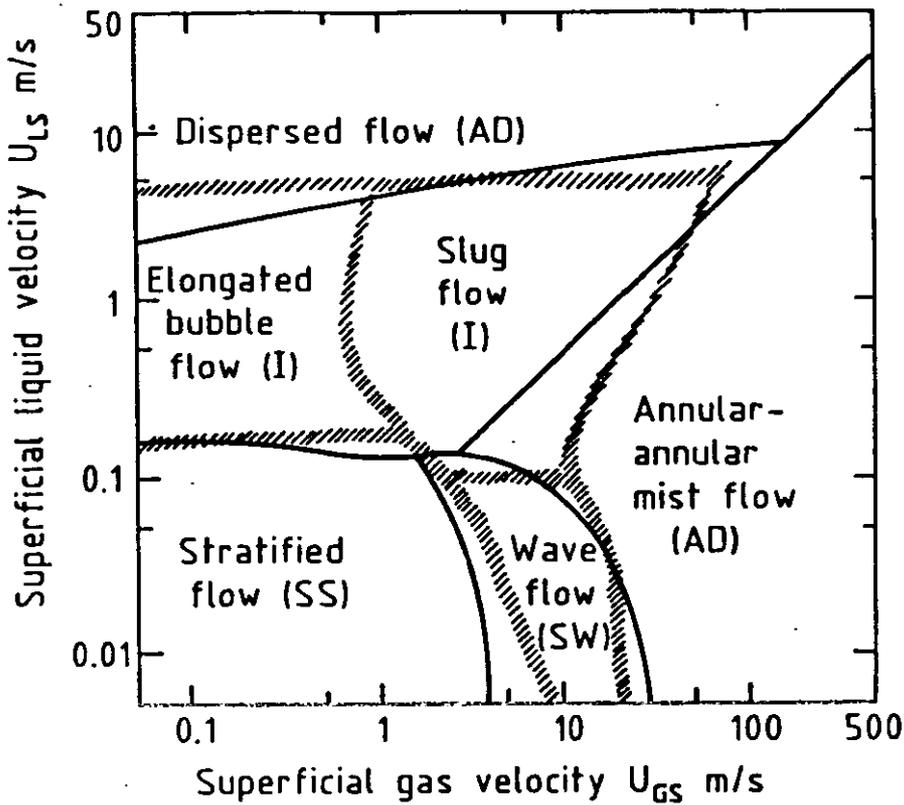


Fig 2a Flow Regime Map for Natural Gas/Oil (68bar) Ref [3]

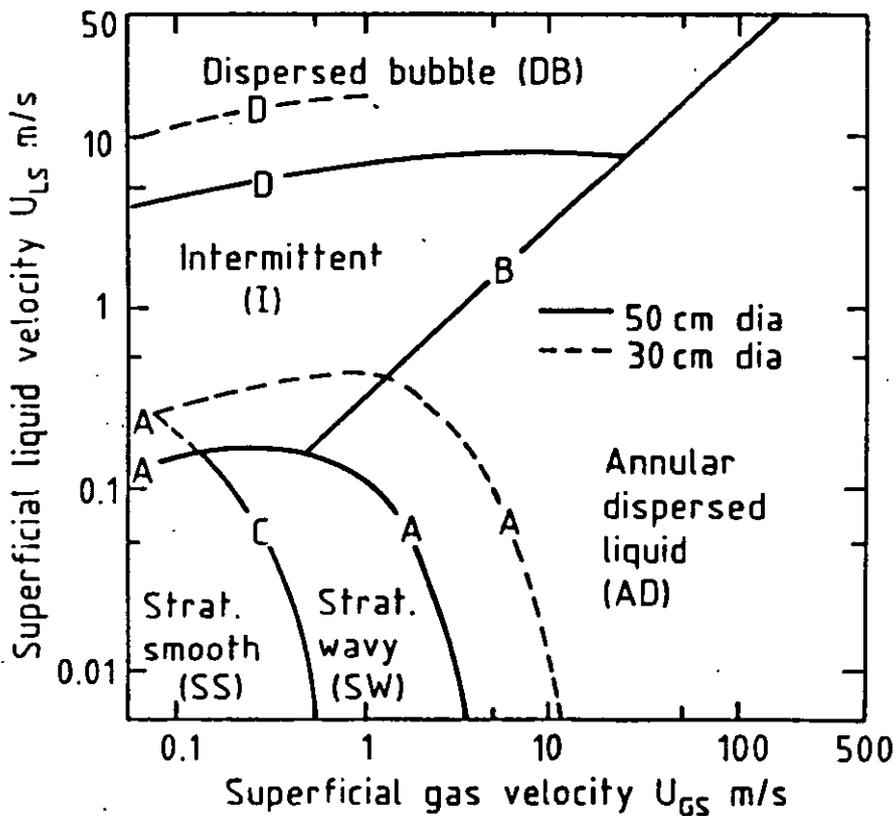
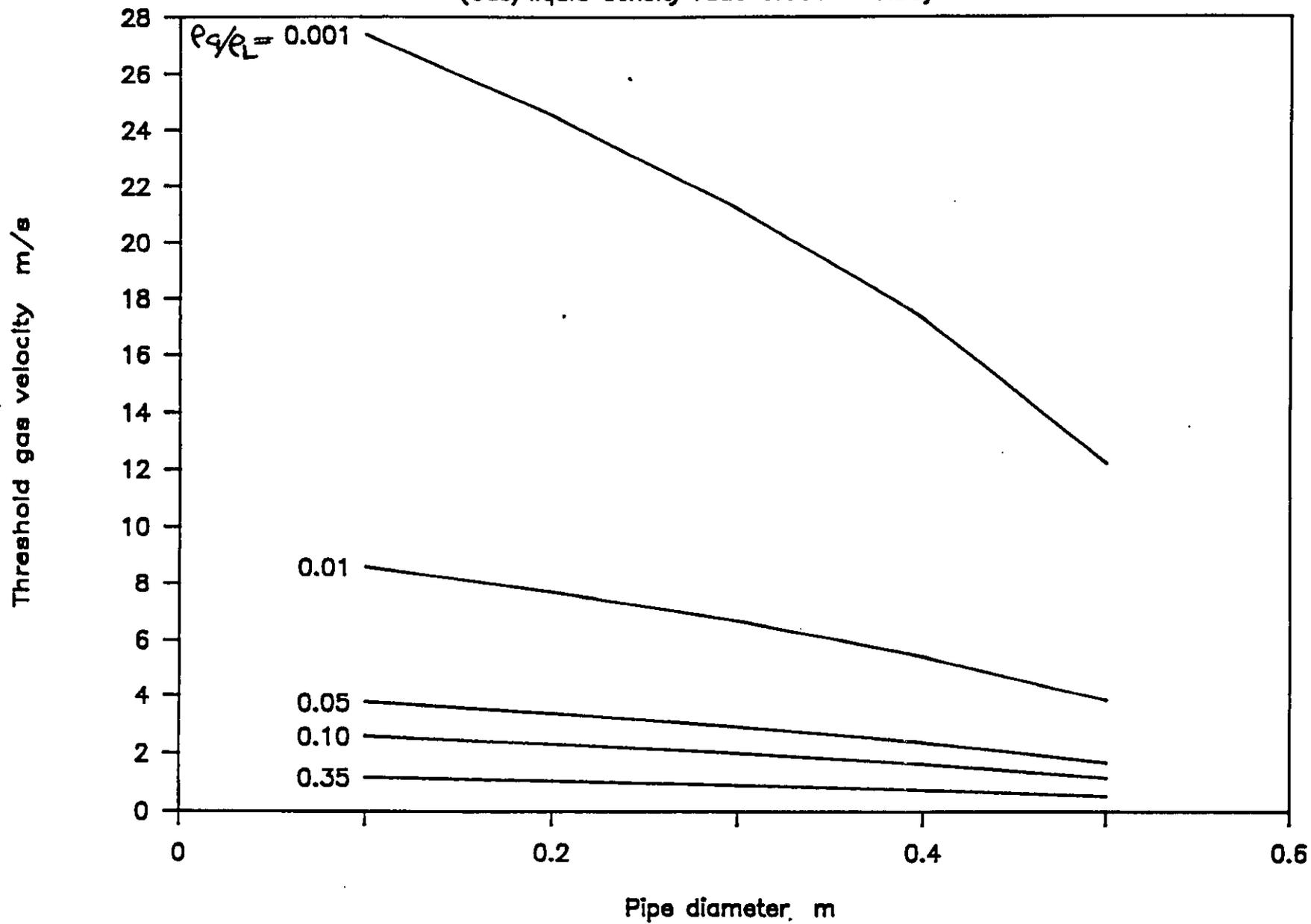


Fig 2b Flow Regime Map for Air/Water (Ambient pressure) Ref. [3]

Fig. 3. Threshold : liquid accumulation

(Gas/liquid density ratio 0.001 - 0.35)



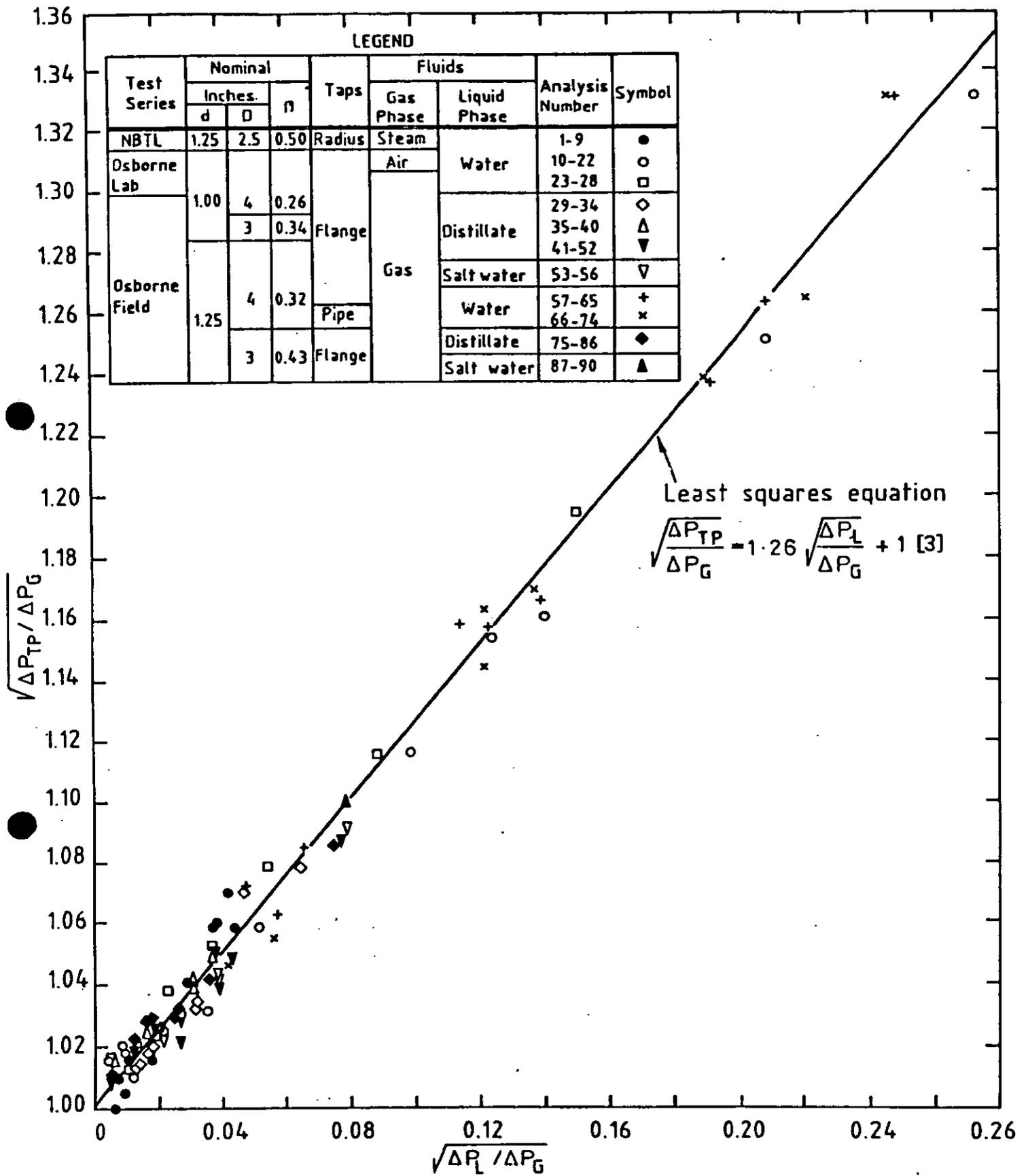


Fig 4 Correlation of Murdock's [10] Data

Fig. 5. Two-phase multiplier variation

(cf Murdock, Chisholm & Lin at 62 BAR)

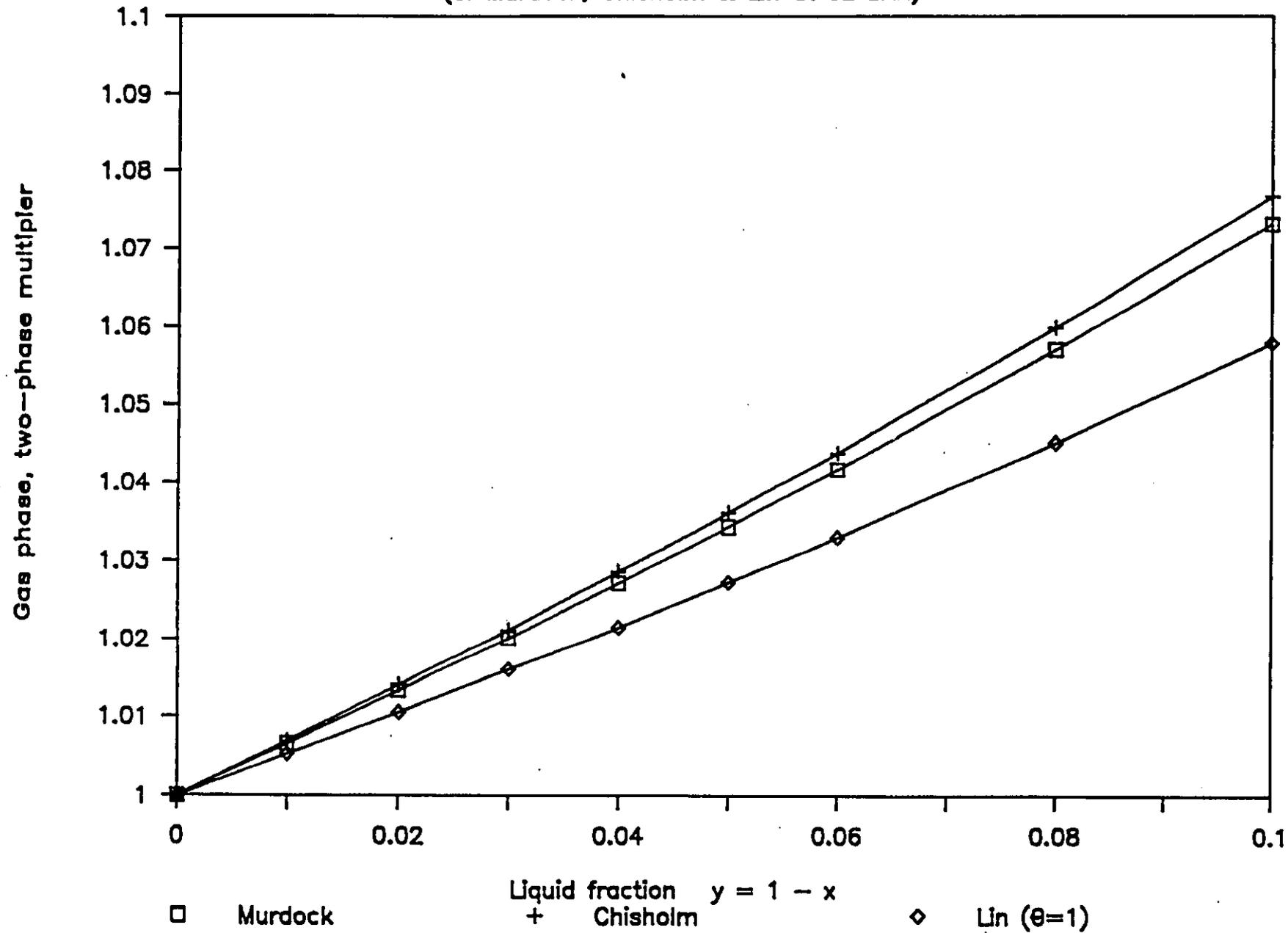


Fig. 6. Two-phase orifice plate corr'ns
(cf Lin's corr'n with Murdock & Teigen)

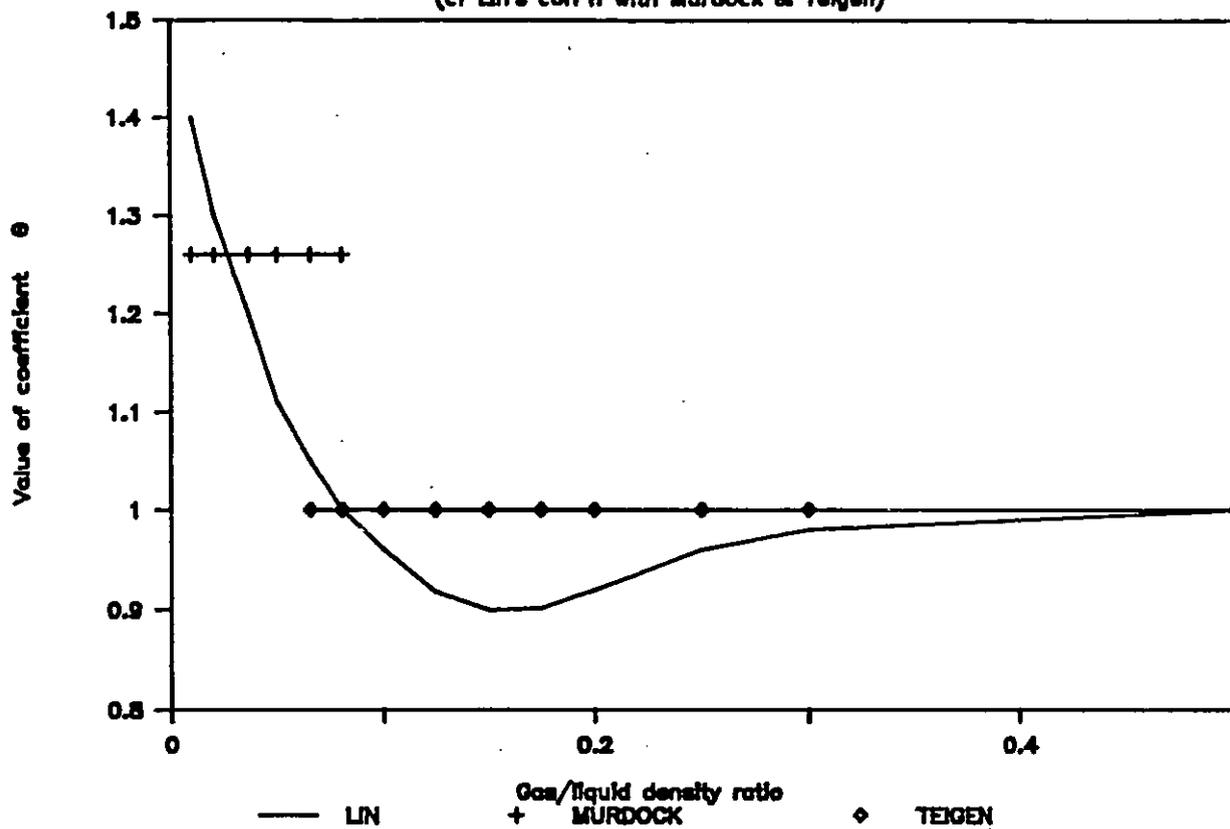


Fig. 7. Two-phase actual gas flowrate
(Full scale compared with two models)

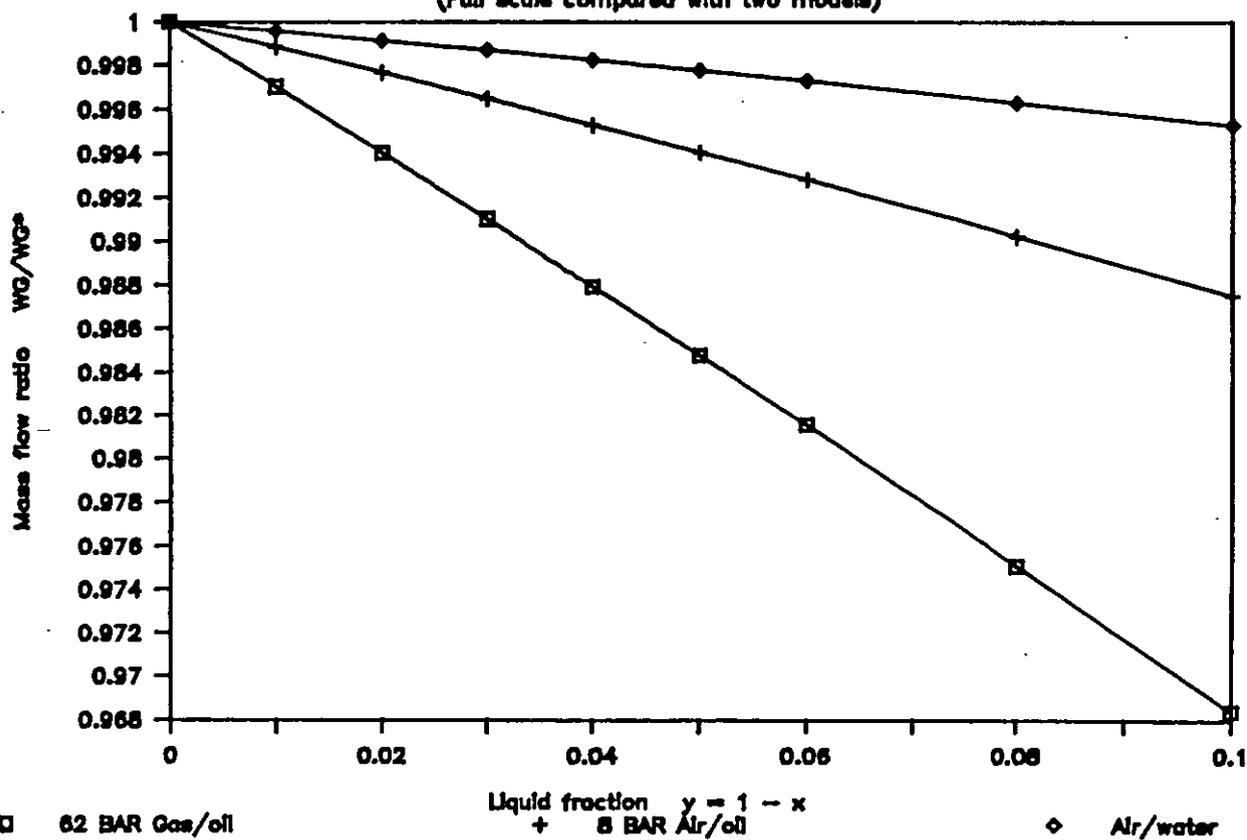


Fig. 8a. Two-phase flowrate of mixture
(Comparison of Murdock & Ln corr'ns.)

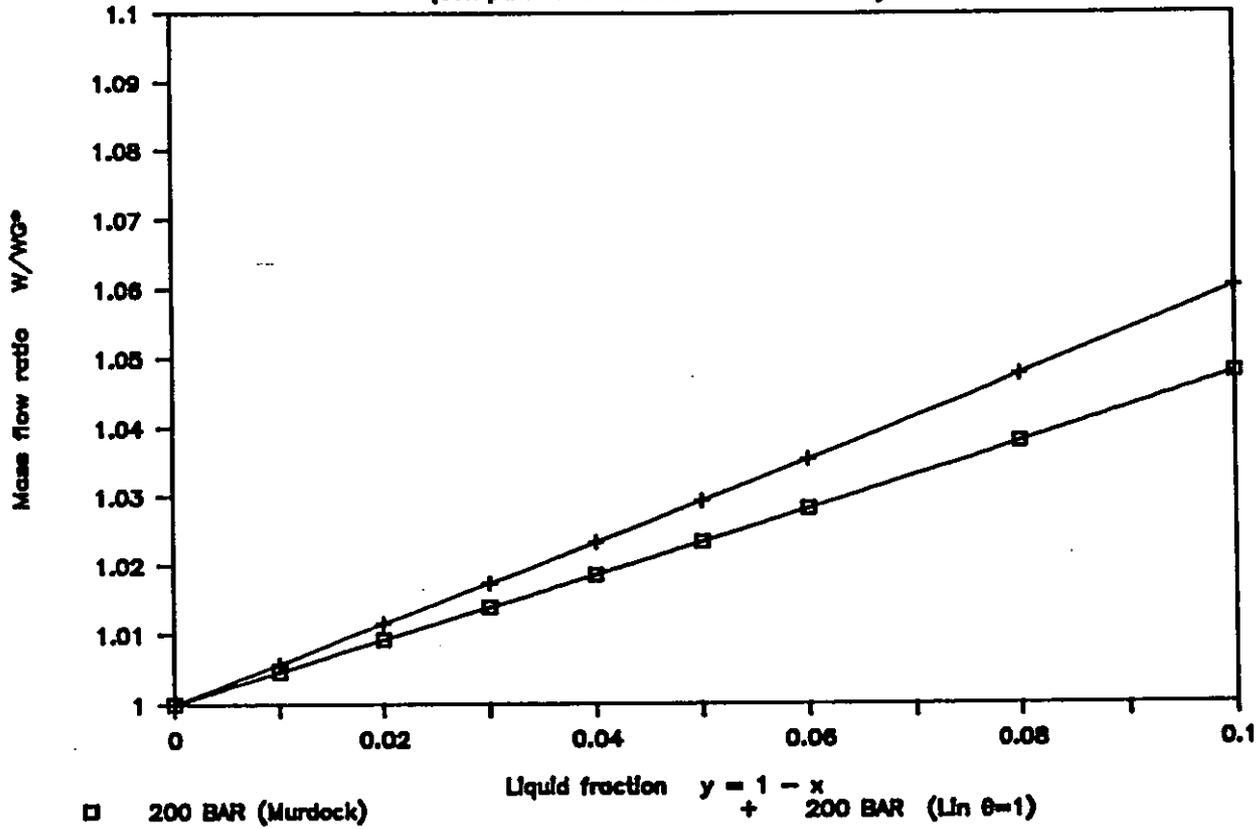


Fig. 8b. Two-phase flowrate of mixture
(Comparison of Murdock & Ln corr'ns.)

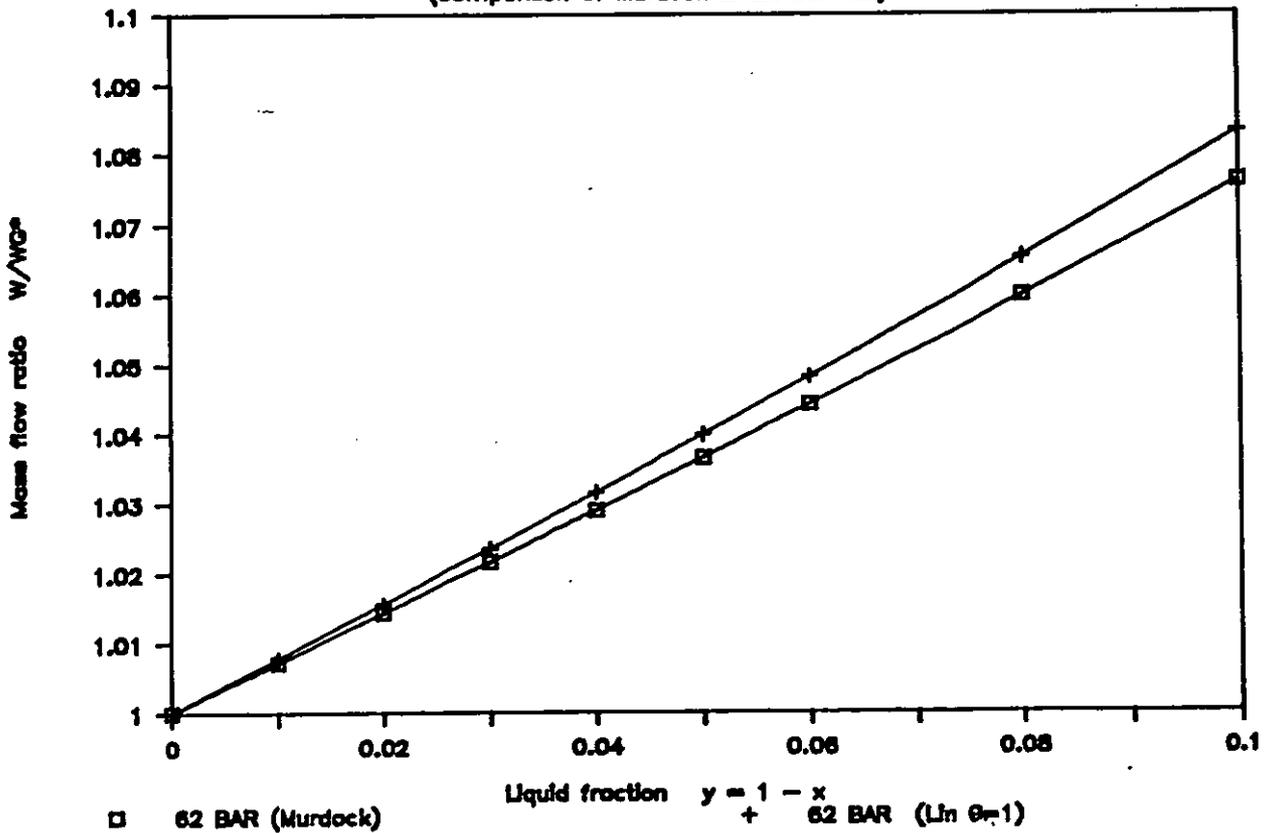


Fig. 9a. Total flowrate of hydrocarbons
(Water, condensate and gas at 200 bar)

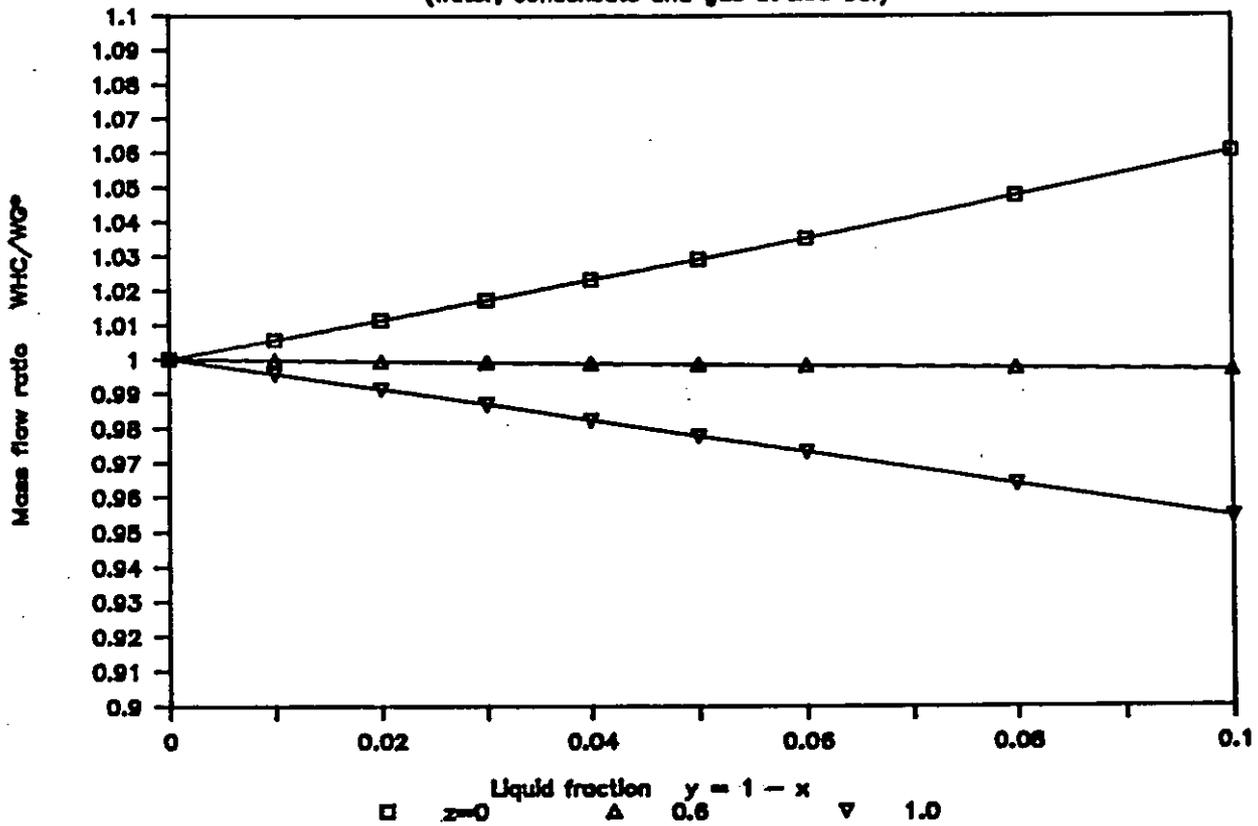
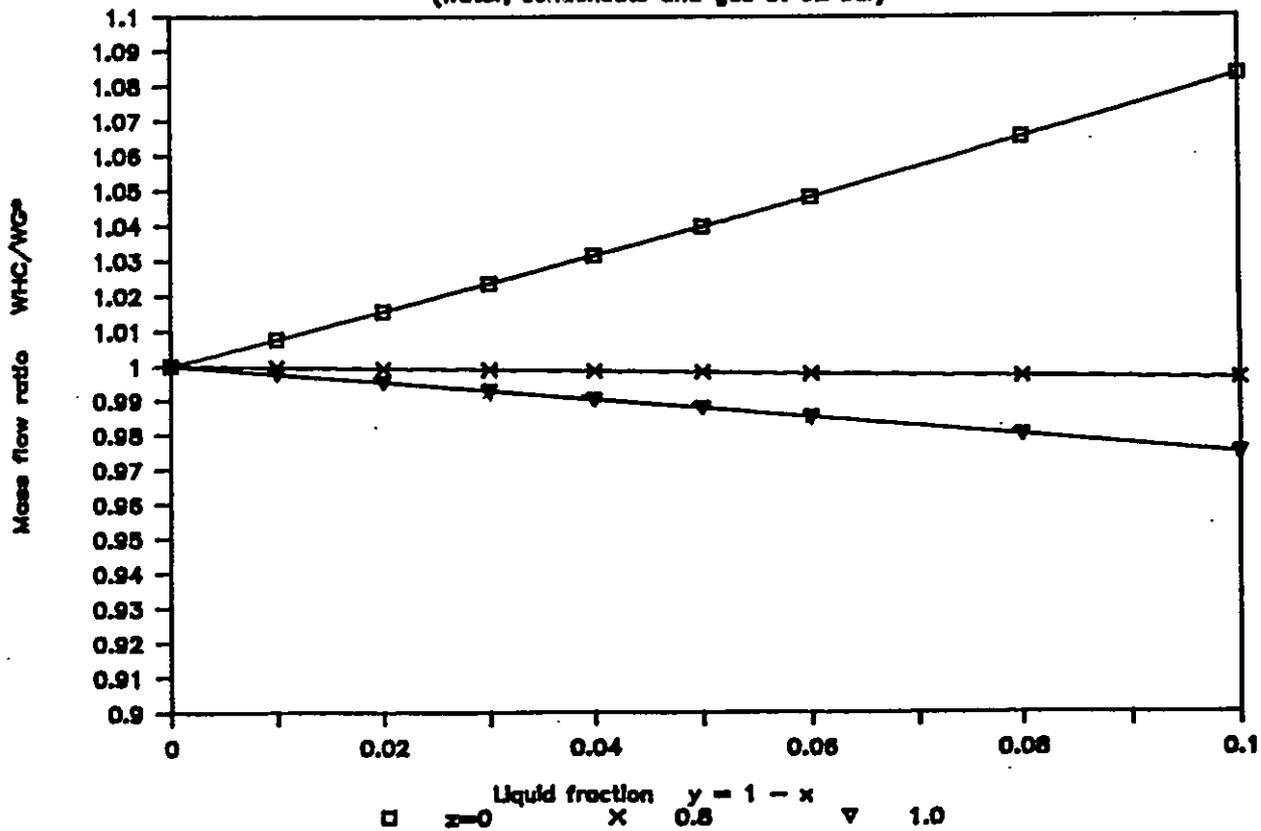


Fig. 9b. Total flowrate of hydrocarbons
(Water, condensate and gas at 62 bar)



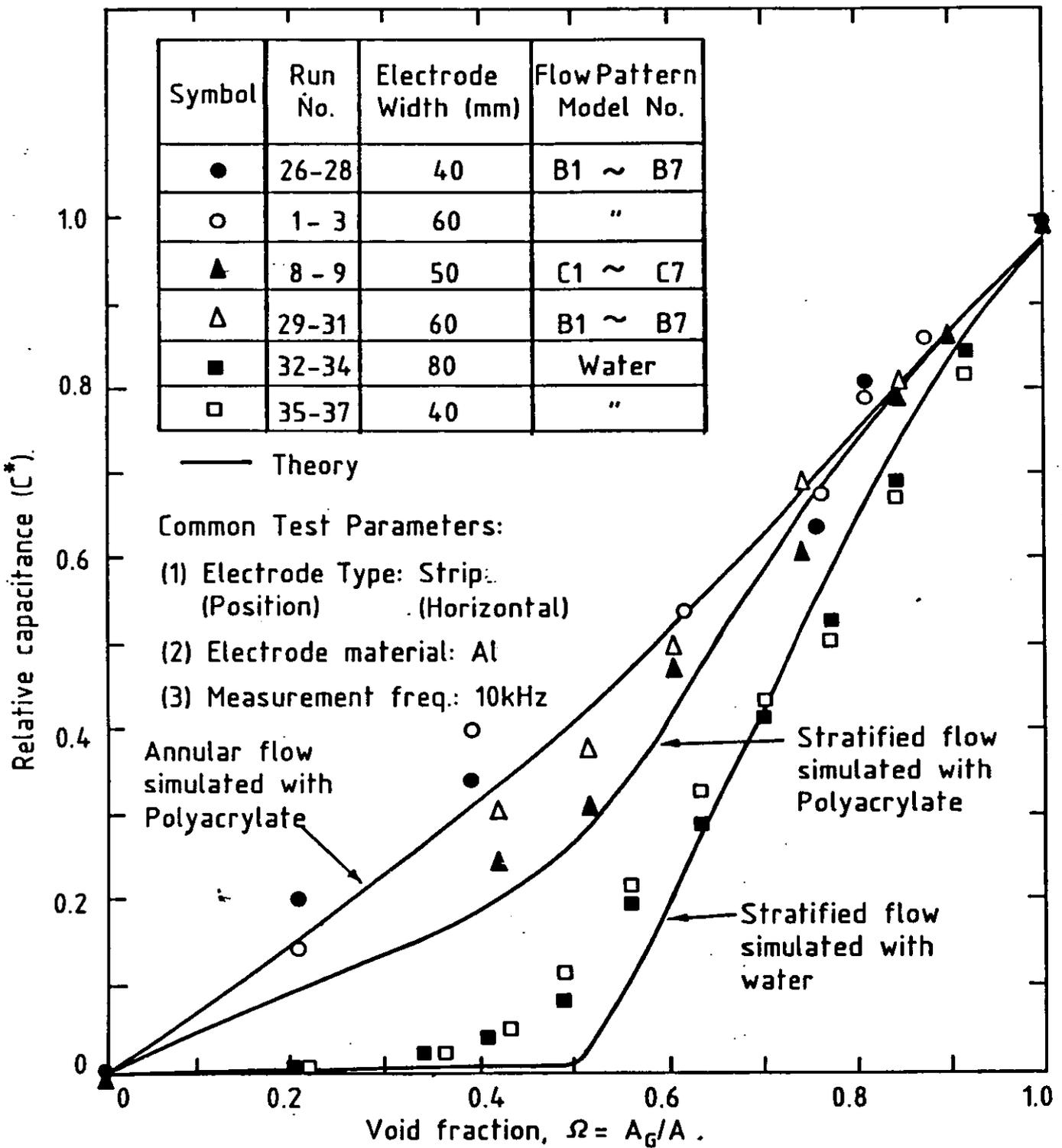
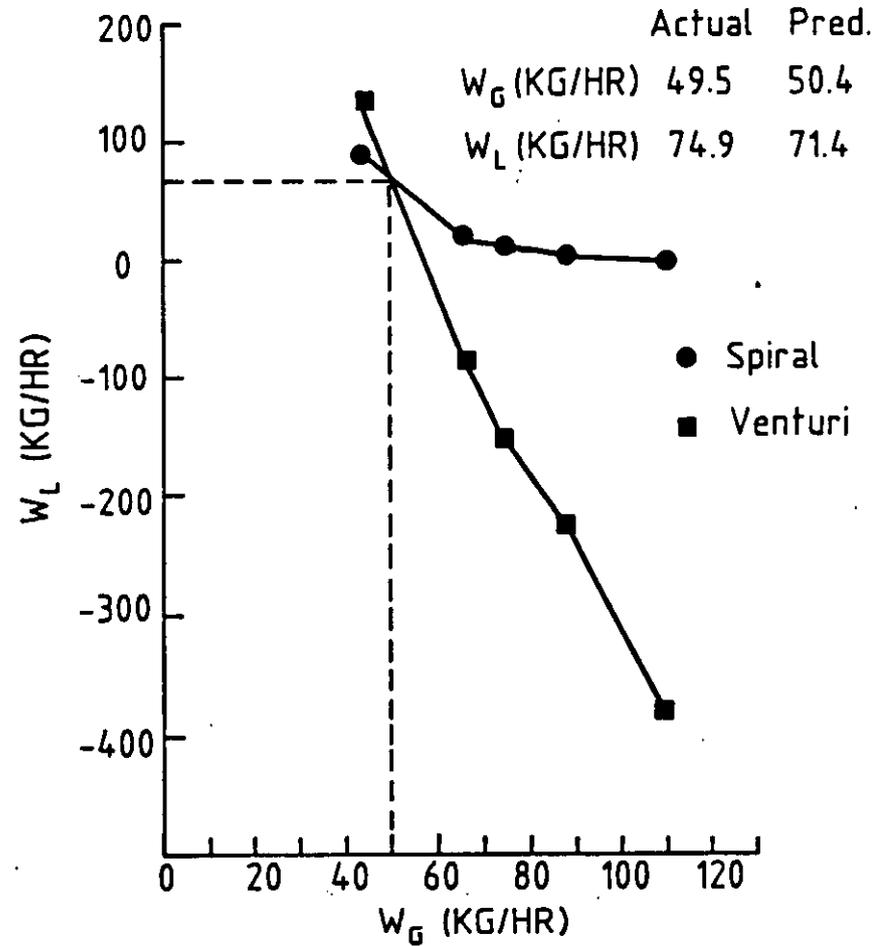
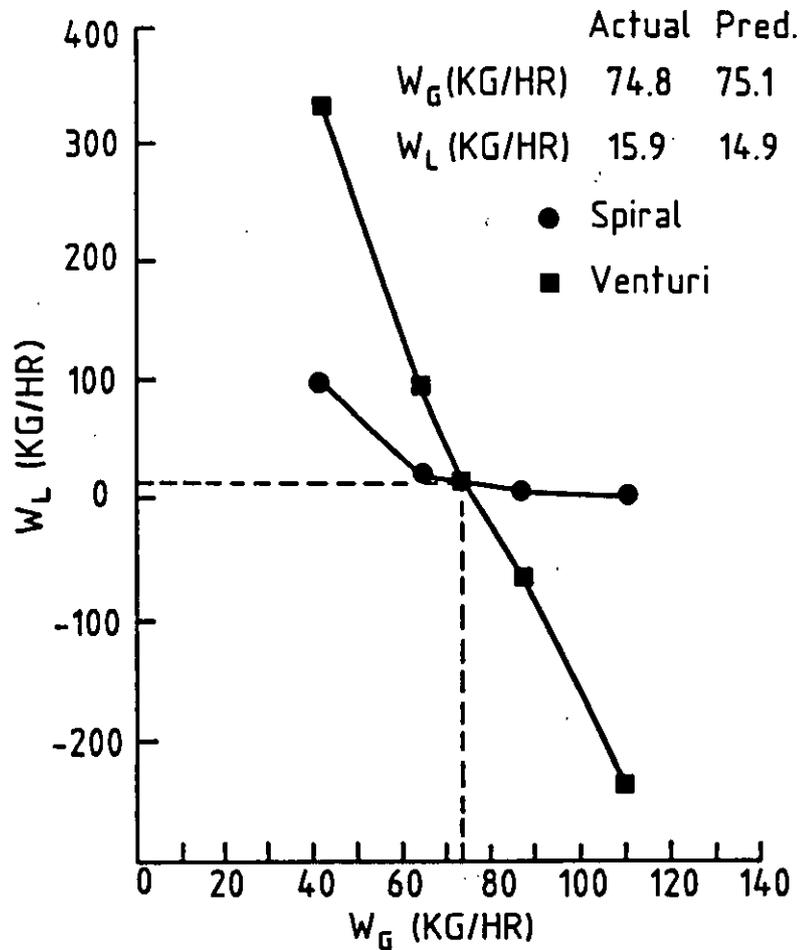


Fig 10 Effect of Geometry and Material on Relative Capacitance (Static Model Tests Ref [14])



Figs. 11a and 11b Two Typical W_L Versus W_G Plots from Combination
(Twisted Tape with Venturi Meter Ref [15])

NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

**NORTH SEA FLOW METERING
WORKSHOP**

13 - 15 October 1987

Stavanger Forum, Stavanger

**DEFLECTION OF ORIFICE PLATES AT HIGH
DIFFERENTIAL PRESSURE**

by

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**Deflection of Orifice Plates at High
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SUMMARY

This paper describes the work carried out at Chr. Michelsen Institute in Bergen to investigate experimentally, the deflection of orifice plates under varying Differential Pressure (DP) conditions.

The project was sponsored by Statfjord Division, and involved the construction of a full scale test rig with components identical to those used on meter stations in the Statfjord Field.

The purpose of the test was to prove that the theoretical formula used by "Jepson and Chipchase" to calculate orifice plate deflection, was equally valid when applied to actual offshore equipment, and thence to establish the actual levels of measurement uncertainty at flow conditions up to 1000 mbar.

INTRODUCTION

During the latter part of 1985, Mobil (MENI) as operator for the Statfjord Fied. started Gas Sales to buyers in the UK and Germany.

Metering of the gas was achieved by four DANIEL gas metering stations, one on platforms A and C, and two on platform B (one of which was dedicated to UK gas export).

The configuration and capacity of each of these meter stations is shown in table 1.

TABLE 1. Statfjord meter station capacity.

Station	No of Tubes (Runs)	Capacity / Tube (Mm3/Day)	Station Capacity (Mm3/Day)
A	3	3.8	7.6
B	2	5.7	5.7
C	2	5.7	5.7
UK	2	3.8	3.8

During the early months of gas export, Mobil had on occasions problems in meeting daily gas delivery requirements, owing to the limited capacity of their meter stations.

Such problems were generally caused by one or more of the following factors:

- reservoir management demands (i.e. prioritying export from one platform only).
- unplanned shutdowns
- planned shutdowns

The options which were considered for resolving this capacity problem were:

1. Installation of additional meter tubes on all platforms.
2. Use the spare meter run.
3. Increasing the range of the DP cells.
4. Increasing orifice plate Beta Ratio's.

Option number 1. was evaluated but rejected because of cost, weight and space restrictions.

Option number 2. could be used in the short term, but would jeopardise the reliability and maintainability of the meter stations.

Option numbers 3 and 4 could be easily applied, but would contravene existing NDP regulations which limit DP to 500 mbar and Beta Ratios to 0.6.

Of these four options, the most attractive (from an operating standpoint) was 3., if approval could be obtained from the appropriate Norwegian and British authorities.

With that thought in mind, Mobil approached CMI, early in 1986, to inquire about the possibility of undertaking full scale test to investigate the deflection of orifice plates under flow conditions exceeding 500 mbar.

If it could be established, that the amount of deflection at high DP was less than 1% and that the mass flow measurement error was less than 0.1% then Mobil felt that they would have a good chance of obtaining relaxation from current authority requirements.

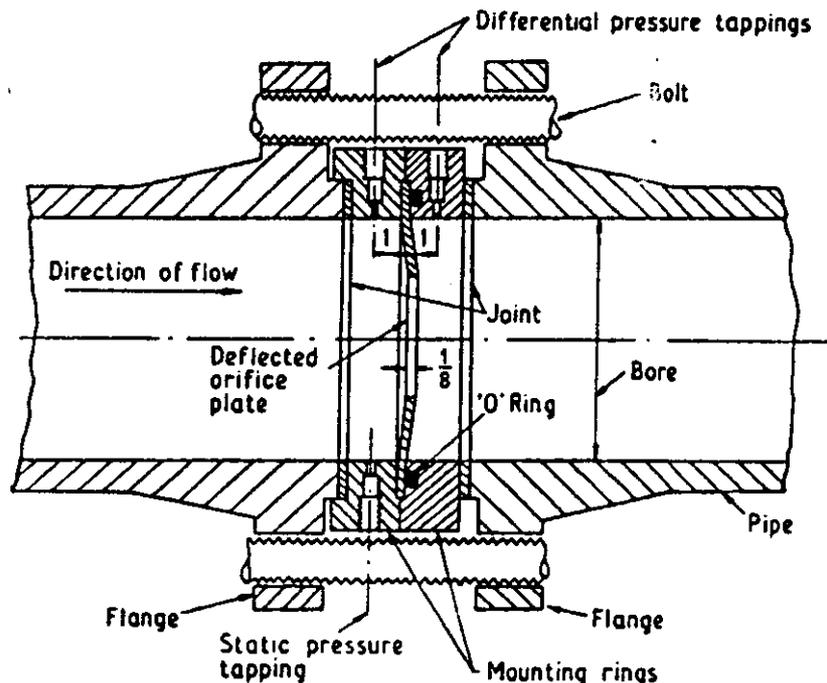
TECHNICAL BACKGROUND

Present regulations for fiscal gas metering, both in Norway and the United Kingdom, require that the range of the differential pressure for orifice plate measurement in fiscal metering systems to be limited to 500 mbar and 0.6 Beta Ratio. In the United Kingdom, however, Department of Energy guidelines provide allowance for exceeding the 500 mbar limit, if the total orifice plate deflection is less than 1%, and the mass flow measurement error is less than 0.1%.

In November 1985 MOBIL Gas Dispatch Centre carried out a calculation study into increasing the Differential Pressure measurement of all the gas metering systems on the Statfjord platforms. This increase was required to improve the operational flexibility of gas sales from the Statfjord field.

The orifice plate deflection calculations were based on a formula given by Messr. Jepson and Chipchase in a paper published in the Journal of Mechanical Engineering in 1975.

The Jepson and Chipchase formula allows calculation of both deflection and associated flow error for various Beta Ratio plates. The original research was carried out by the British Gas at their Killingworth research station in The North East of England, and utilized plates mounted rigidly between flanges. This experimental work however, involved working at differential pressures from 0 - 120 mbar. (Figure 1.)



Note: all dimensions are inches

Figure 1. Jepson and Chipchase Orifice-plate fixing arrangement.

The orifice fittings used in the Statfjord gas metering stations are DANIEL Senior Carriers. The seal rings used in these orifice carriers are made of stainless steel and comply fully with ISO 5167, Rev. 80. These seal rings do not provide the same rigid mounting as obtained for the flange mounted plates tested by Jepson and Chipchase. It was therefore of great interest to verify if the Jepson and Chipchase formula is equally valid for the type seal rings used offshore, and operating at differential pressure up to 1000 mbar.

THE TEST RIG

A test rig was designed to simulate as far as possible the conditions found on offshore gas meter stations, and comprised the following main parts: (Figure 2)

- Air reservoir and supply source.
To ensure a controlled air pressure during the tests, a buffer tank with regulated input pressure control was devised.
- 10 inch nominal bore piping.
- DANIEL 10 inch junior orifice carrier.
Pipe and carrier were fitted and flanged using offshore grade material.
- Restriction tube.
To achieve a differential pressure of 1000 mbar across the orifice plate under laboratory conditions, it was necessary to restrict the air flow through the orifice plate. A restriction tube was centered in the 10 inch pipe, leaving only a small clearance (0.8 mm) between the tube and the orifice plate bore.
- Deflection and DP measurement devices.
The DP measurement device was a FOXBORO 823DP d/p Cell TRANSMITTER, and the deflection measuring devices were of the TESATRONIC type linear measuring device.

(A patent for the rig has been applied for.)

Figure 3. shows the transducers used for deflection measurements, and also indicates placement of these transducers (4) on the orifice plate under test.

The DP-cell and the deflection measurement transducers were connected to a DATA 6000 data logger, capable of logging more than 2000 samples at high speed to internal memory, from each input channel in parallel, during a test run (approx. 1 minute).

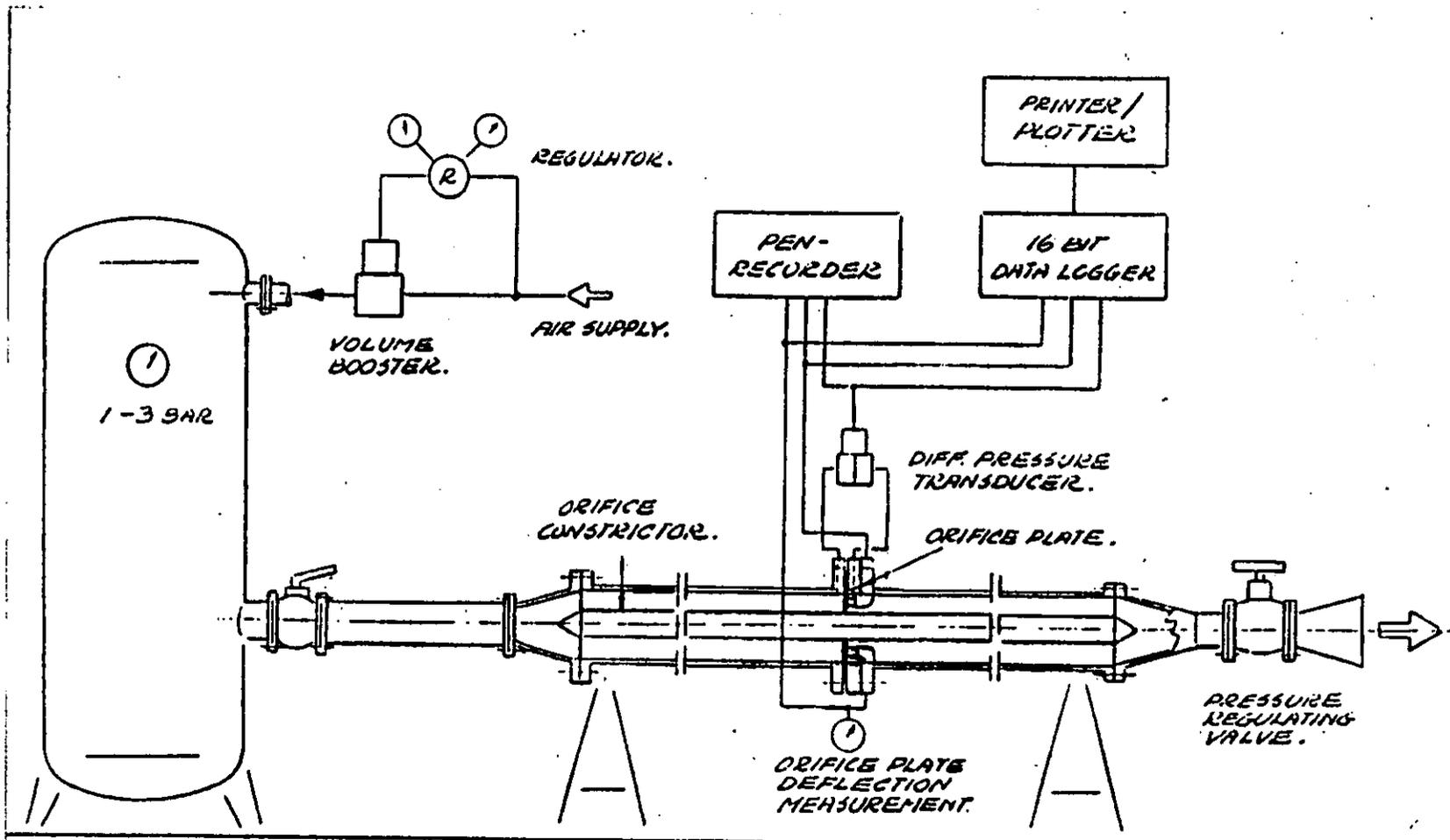


Figure 2. General arrangement of test rig.

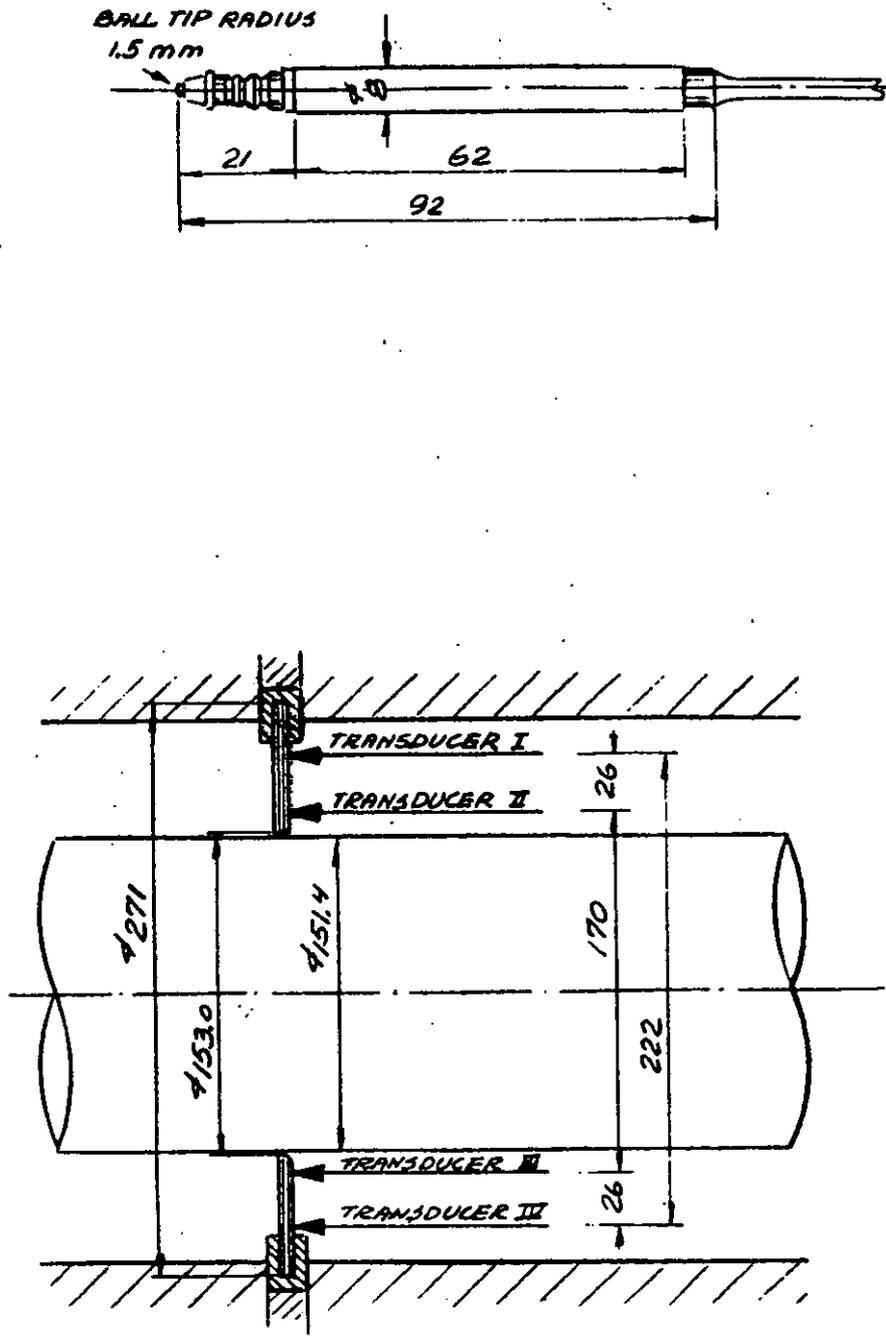


Figure 3. Displacement transducers - Details.

After each run, data from the data logger was transferred to a Hewlett Packard 9816 series 200 desktop computer, for data processing and presentation of tables and graphs.

A sketch showing the theoretical deflection form of the orifice plate is shown in Figure 4. The displacement value Y_{max} was derived during the test by linear interpolation under the assumption of flat plate theory.

TESTS PERFORMED

Tests were carried out with a combination of 3 seal rings, each of a different type, and 3 orifice plates with different properties. Figure 5. illustrates how the seal rings fitted into the carrier.

Each combination was tested 4 times, twice with increasing d/p (0 - 1000 mbar) and twice with decreasing d/p (1000 - 0 mbar).

Referring to Figure 2., the following was done before each of the above tests:

- . Buffer tank pressure was set to establish 1000 mbar across the orifice plate, with Pressure Regulating Valve fully open.
- . Data logger was "armed".

Test run - Increasing method (0 - 1000 mbar):

- . Pressure Regulating Valve was fully closed.
- . Air valve between buffer tank and pipe was fully open.
- . Trigger signal to data logger and opening/closing device on Pressure Regulating Valve.

The data logger now started to collect data, while the Pressure Regulating Valve was slowly turning to fully open. The opening/closing device was set to fully open the the valve within the timespan of the data logging period (approximately 1 minute). The d/p cell signal and the transducer signals were all stored in the data logger memory, for further processing.

Test run - Decreasing method (1000 - 0 mbar):

- . Pressure Regulating Valve was fully closed.
- . Air valve between buffer tank and pipe was fully open.
- . Trigger signal to data logger and opening/closing device on Pressure Regulating Valve.
- . Shut of air supply to buffer tank.

In this case the opening/closing device was set to open the valve at maximum speed. When the Pressure Regulating Valve was fully open, the air supply to the buffer tank was shut of. The pipe pressure started to drop, and the d/p cell signal reached zero within the timespan of the data logging period (approximately 1 minute).

The d/p cell signal and the transducer signals were all stored in the data logger memory, for further processing.

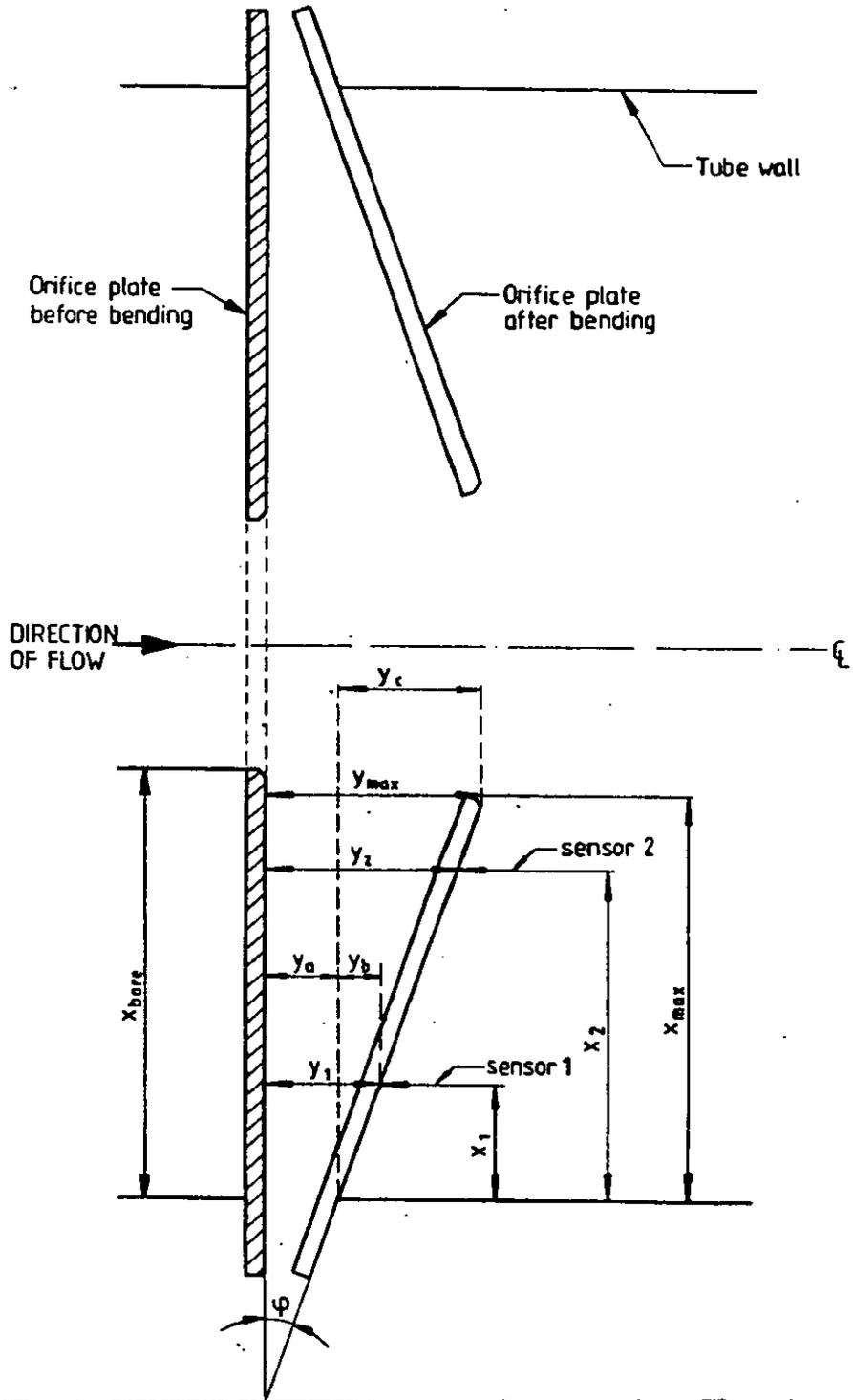


Figure 4. Principle of plate deflection measurement.

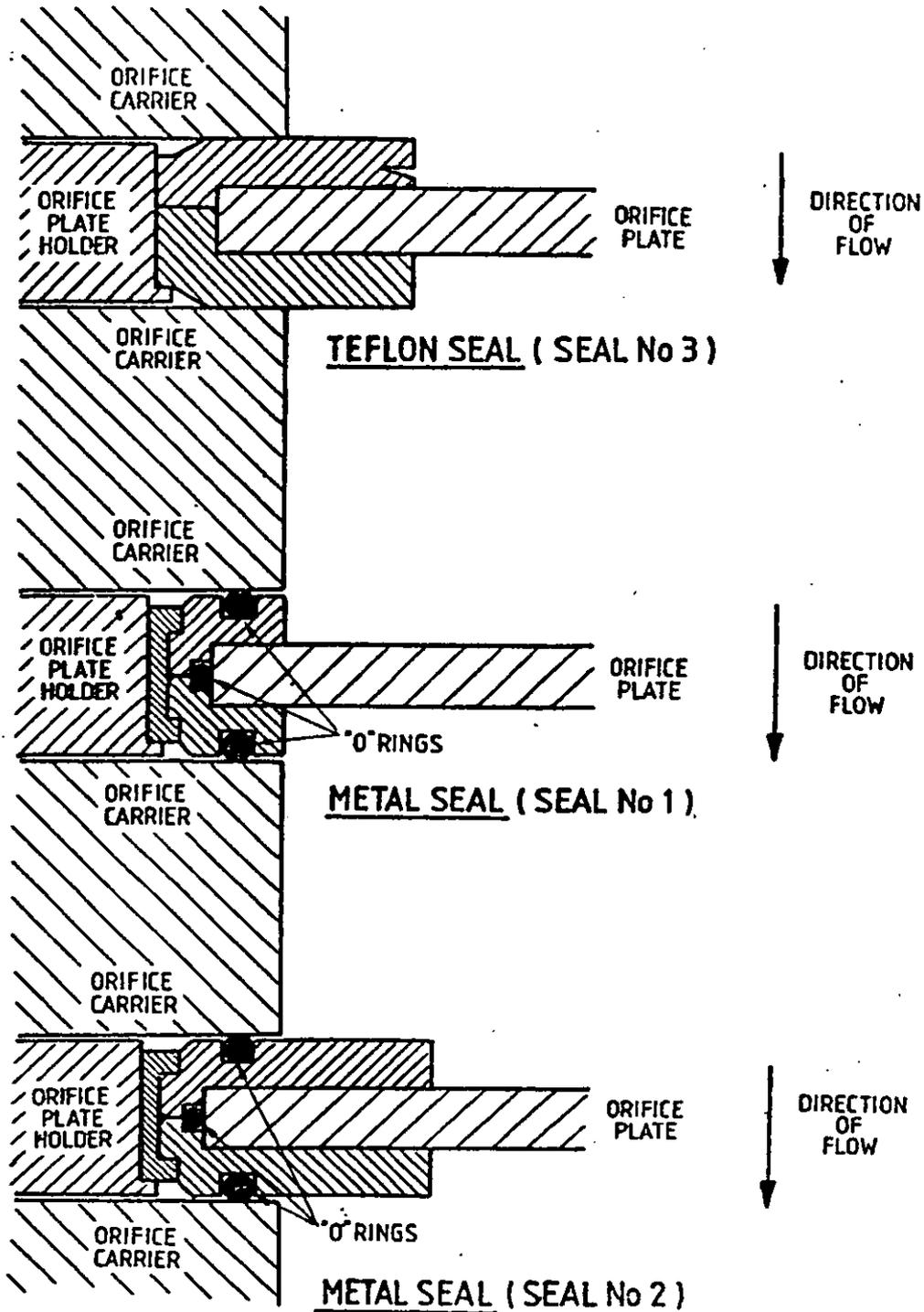


Figure 5. Different seal ring arrangements.

RESULTS

Three different orifice plates were tested (ESAS-M076 6.177mm thick, ESAS-M075 6.197mm thick, DANIEL-95685 6.475mm thick). Each of them mounted in three different seal rings. (Metal-316S/S 256mm I/D, Metal-316S/S 224mm I/D and Teflon 224mm I/D, all from DANIEL).

Some examples of the graphs of orifice plate deflection, measured and calculated according to Jepson and Chipchase, are presented in the Figures 6, 7, 8, 9 and 10.

Christian Michelsen Institute, 17 Nov 1986
Orifice plate deflection vs. differential pressure, Run no. 1.11

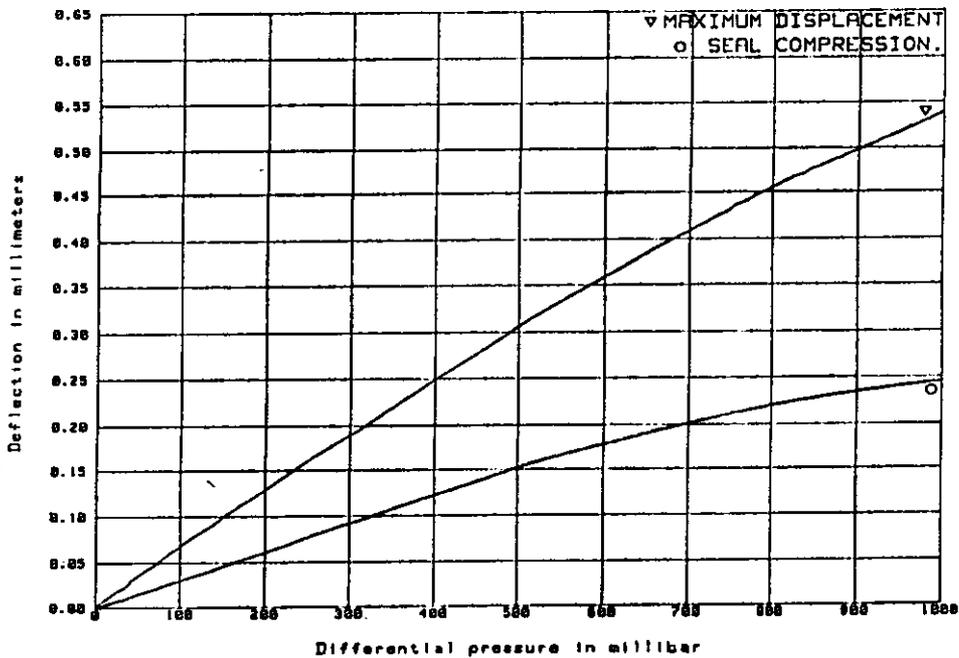


Figure 6. Measured deflection of M076-ESAS plate mounted in metal seal 316 S/S, 256mm I/D. (Run 1.11)

Christian Michelsen Institute, 17 Nov 1986
Orifice plate deflection vs. differential pressure, Run no. 1.11

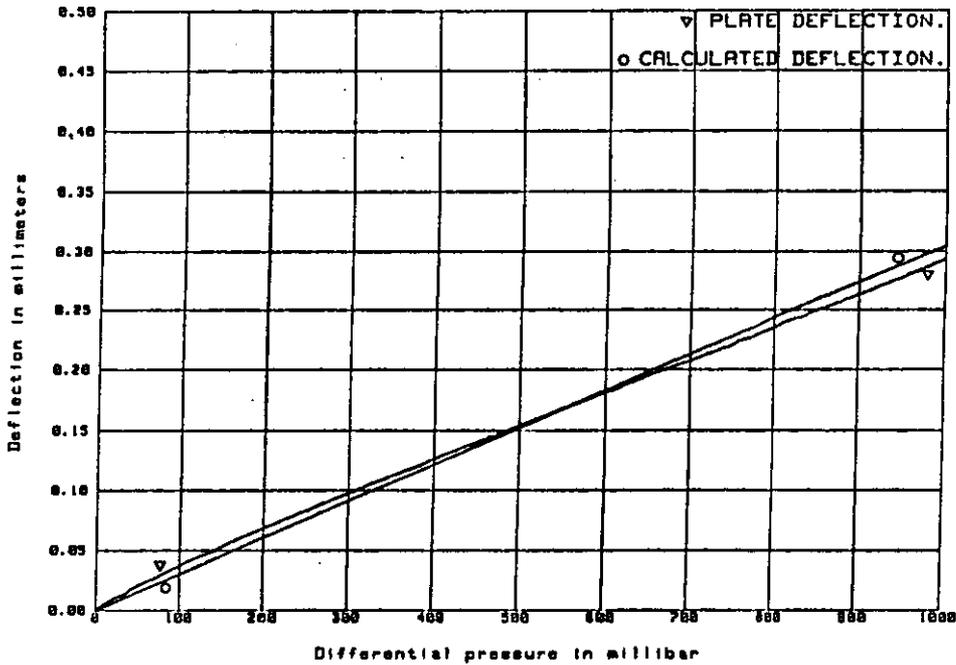


Figure 7. Measured and calculated deflection of M076-ESAS plate mounted in metal seal 316 S/S, 256mm I/D. (Run 1.11)

Christian Michelsen Institute, 19 Nov 1986
Orifice plate deflection vs. differential pressure, Run no. 2.11

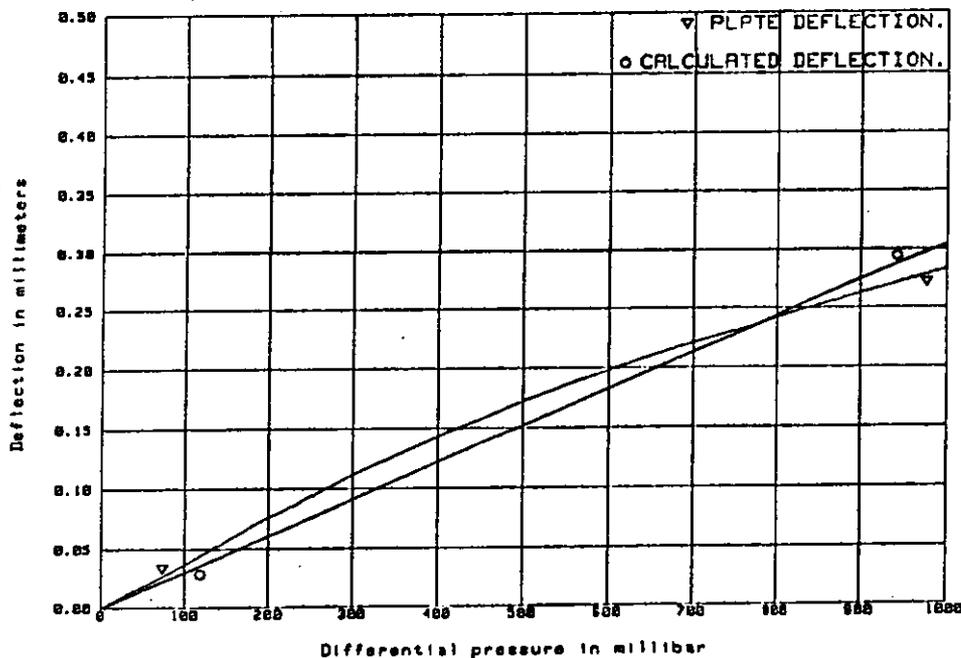


Figure 8. Measured and calculated deflection of M076-ESAS plate mounted in metal seal 316 S/S, 244mm I/D. (Run 2.11)

Christian Michelsen Institute, 22 Aug 1986
Orifice plate deflection vs. differential pressure, Run no. 3.11

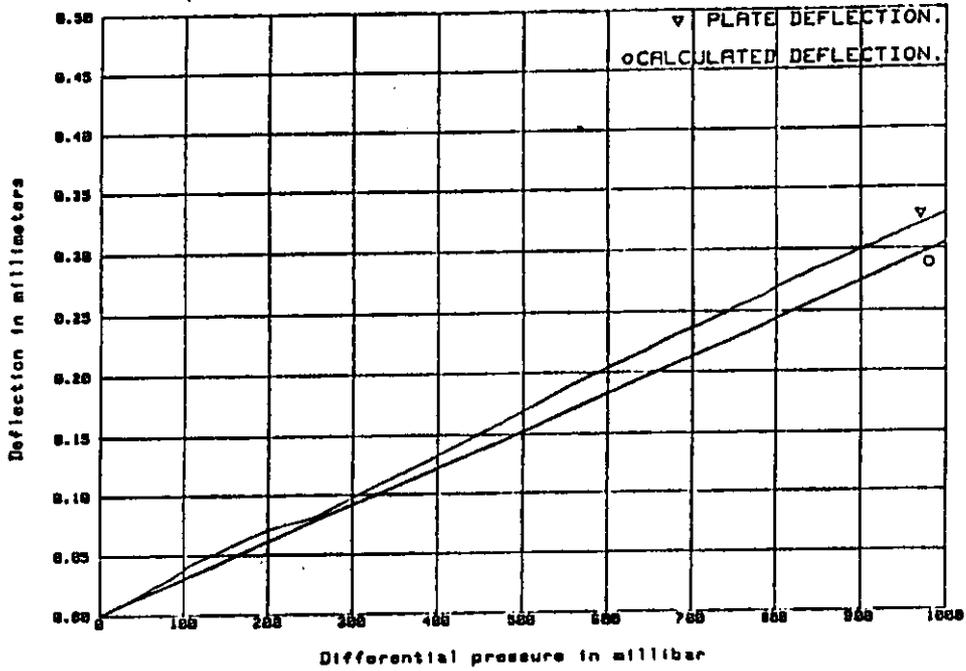


Figure 9. Measured and calculated deflection of M076-ESAS plate mounted in Teflon seal, 224mm I/D. (Run 3.11)

Christian Michelsen Institute, 18 Nov 1986
Orifice plate deflection vs. differential pressure, Run no. 1.31

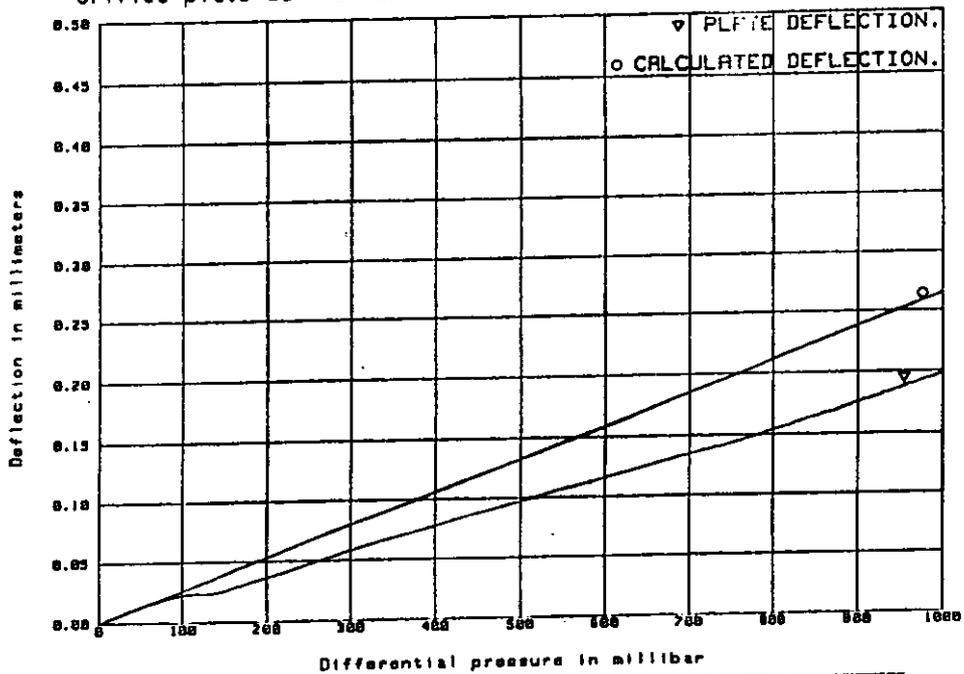


Figure 10. Measured and calculated deflection of 95658 - DANIEL plate mounted in metal seal 316 S/S 256mm I/D (Run 1.13)

The results from our measurements are summarized in table 2.

Table 2.

RESULTS

COMPARISON OF ACTUAL DEFLECTION AGAINST THEORETICAL DEFLECTION

SEAL RING	ORIFICE PLATE		
	ESAS (6.177 THICK)	ESAS (6.197 THICK)	DANIELS(6.475 THICK)
1. METAL 258 MM I/D	VERY CLOSE TO THEORETICAL DEFLECTION	20% LESS THAN THEORETICAL DEFLECTION	20% LESS THAN THEORETICAL DEFLECTION
2. METAL 224 MM I/D	CLOSE TO THEORETICAL DEFLECTION (± 10%)	33% LESS THAN THEORETICAL DEFLECTION	40% LESS THAN THEORETICAL DEFLECTION
3. TEFLON 224 MM I/D	15% GREATER THAN THEORETICAL DEFLECTION	15% GREATER THAN THEORETICAL DEFLECTION	CLOSE TO THEORETICAL AT 1000 MILLIBAR, 15% GREATER AT 500 MILLIBAR

CONCLUSION

From the results of the tests it could be seen that each seal ring/orifice plate combination performed in a different way. Of the three seal rings however, the following comments can be made:

Seal Ring 1. (Metal 256mm I/D)

It was the only seal ring which matched the orifice plate carrier.

Seal Ring 2. (Metal 224mm I/D)

The inside diameter of the seal ring protruded into the carrier bore, giving additional support to the orifice plates. The results obtained from this seal ring were repeatable, although significant seal movement was experienced at low DP, owing to use of old "O"-rings.

Seal Ring 3. (Teflon 224mm I/D)

The inside diameter of the seal ring protruded into the carrier bore, initially providing additional support to the orifice plate. On repeated tests this support was much less evident, due the plastic deformation of the Teflon.

Whilst the results from Seal Ring 2 and 3 are most interesting, such seals would not have been used in a similar offshore metering station, because their inside diameter protrude into the bore of the carrier.

In conclusion however, the results of the tests (with particular reference to Seal Ring 1.) have established the following:

1. The Jepson and Chipchase formula for orifice plate deflection under high differential pressure, will give a worst case result if the orifice plate is used with a metal seal ring.
2. Increases in the thickness of standard orifice plates do not significantly reduce orifice plate deflection.
3. As DP increases (max 1000 mbar) the Jepson and Chipchase formula will increasingly predict a deflection value in excess of the actual value.
4. The use of Teflon seal rings will generally give less overall plate displacement (i.e. seal ring + orifice plate), but may give an orifice plate deflection 15% greater than that calculated by using the Jepson and Chipchase formula.

SUMMING UP

Although the tests described in this paper were motivated by operational needs, the consequence of our findings have probably more impact in the future design of new meter stations.

If for example authority approval was obtained to operate meter stations at DP levels up to say 1000 mbar, the potential savings for the industry could be enormous in terms of:

- Weight Savings
- Equip. Cost Savings
- Operating Cost Savings
- Spares Cost Savings

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REAL-GAS EFFECTS IN THE EXPANSIBILITY FACTOR FOR SUBSONIC
DIFFERENTIAL PRESSURE FLOW METERS AT HIGH PRESSURE

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3.4

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ABSTRACT

General and exact expressions for the expansibility factor, including arbitrary real-gas corrections, are derived. Further analyses are provided by the introduction of the equation of state on virial form, in which the second and third virial coefficients are calculated from a prototype cubic equation of state.

Important cancellations between real-gas effects, which put equations of state to a severe test at high pressure, are revealed.

The exact result raises doubts about the general applicability of the current ISO standard in a high accuracy approach for orifice measurements of gases with arbitrary composition, at high as well as at low pressure.

1. INTRODUCTION

The international standard ¹ for natural gas flow measurements by orifices, nozzles and venturi tubes is based on a polytropic equation of state for the isentropic gas flow. This description is exact for an ideal gas. For custody transfer at pressures typically exceeding 100 bar, the polytropic approach is not justified even at supercritical temperatures, if high measurement accuracy is an objective.

Essentially two methods for the inclusion of real-gas effects have been presented in the literature. The first one ² underlies the polytropic approach, assuming that real-gas effects can be taken into account by defining an isentropic exponent κ . Obviously, such an exponent is pressure-dependent, complicating calculations by creating the necessity for using different exponents in different ranges of pressure. Also, it is not obvious that the theory of flow through contractions can be consistently modified by ad hoc changes of the isentropic exponent. The recommended practice ¹ is to replace κ by the ratio γ between specific heats if κ is not known. This may have contributed to the widespread misconception of identifying κ with γ . The second approach ³, introduced for sonic nozzles, is based on a full treatment of the thermodynamics of the isentropic flow problem, rigorous to the extent that the compressibility (i.e., the equation of state) is well known. This excellent method, employing iterative solution of the entropy and enthalpy equations, has a drawback in a lack of clarity and overview for the practical user, since the results are given by tables and graphs rather than simple formulas.

This paper first develops general expressions for the expansibility factor. The principle of corresponding states is then used to obtain composition-independent predictions for the isentropic equation of state, by calculating virial coefficients from a prototype cubic equation of state, chosen for simplicity as much as for accuracy. Explicit expressions for the expansibility factor, as well as predictions of a general kind, are then obtained by low order corrections to ideality. This paper has thus a didactic purpose, in addition to pointing out the direction for further research.

2. THE EXPANSIBILITY FACTOR

Consider an adiabatic real gas flow without energy loss through an orifice, nozzle or venturi tube, with velocity u depending on the flow cross-section A . Assume that equilibrium thermodynamics applies, and that changes in thermodynamical states are reversible⁴. Conservation of energy is then given as usual by the Bernoulli equation⁵

$$\frac{1}{2} u_1^2 + H(p_1) = \frac{1}{2} u_2^2 + H(p_2) \quad (1)$$

where $H(p)$ is the isentropic enthalpy per mass unit, H_0 being an indefinite constant contribution:

$$H(p) - H_0 = \int_0^p \frac{dp}{\rho} \quad (2)$$

The density ρ and the pressure p is related through an isentropic equation of state, to be considered in detail later. Subscript ₁ will refer to a point upstream of the flow obstacle, while subscript ₂ refers to the center of the orifice or nozzle. The standard derivation of the expression for mass flow rate \dot{m} based on eq. (1) gives then

$$\dot{m} = A_2 C \varepsilon \sqrt{\frac{2 \rho_1 \Delta p}{1 - \beta^4}} \quad (3)$$

where

$$\Delta p = p_1 - p_2 \quad (4)$$

is the differential pressure, β is the ratio of the least hardware limitation of flow radius to pipe radius upstream, and C is the discharge coefficient which will not be discussed in any detail in the present paper. The expansibility factor ε includes real-gas effects in a completely general way, when written on the form

$$\varepsilon^2 = \left(\frac{\rho_2}{\rho_1}\right)^2 \frac{\rho_1}{\Delta p} \frac{1 - \beta^4}{1 - \left(\frac{\rho_2}{\rho_1}\right)^2 \beta^4} \{ H(p_1) - H(p_2) \} \quad (5)$$

For a flow arrangement where Δp is a considerable fraction of the upstream pressure, one now proceeds by calculating $H(p)$ explicitly by an equation of state. In particular, it can be calculated to an arbitrary order in the virial expansion to be introduced in subsequent sections. However, for arbitrary forms of the equation of state this does not necessarily lead to simple analytical expressions.

A considerable simplification occurs in the limit where Δp is small compared to the upstream pressure p_1 . We expand $H(p)$ in a Maclaurin series in Δp around p_1 , using first the integral definition of $H(p)$ in eq. (2). Using also

$$\begin{aligned} \left(\frac{\rho_2}{\rho_1}\right)^2 &= 1 - \frac{2}{\rho_1} \left(\frac{\partial \rho_1}{\partial p_1}\right)_s \Delta p \\ &+ \left[\frac{1}{\rho_1^2} \left(\left(\frac{\partial \rho_1}{\partial p_1}\right)_s\right)^2 + \frac{1}{\rho_1} \left(\frac{\partial^2 \rho_1}{\partial p_1^2}\right)_s \right] (\Delta p)^2 + \dots \end{aligned} \quad (6)$$

we arrive by a straightforward calculation at the result

$$\begin{aligned} \varepsilon &= 1 - \left(\frac{3}{4} + \frac{\beta^4}{1 - \beta^4}\right) \frac{1}{\rho_1} \left(\frac{\partial \rho_1}{\partial p_1}\right)_s \Delta p \\ &+ \left[\left(-\frac{11}{96} + \frac{5}{4} \frac{\beta^4}{1 - \beta^4} + \frac{3}{2} \frac{\beta^8}{(1 - \beta^4)^2}\right) \frac{1}{\rho_1^2} \left(\left(\frac{\partial \rho_1}{\partial p_1}\right)_s\right)^2 \right. \\ &\quad \left. + \left(\frac{5}{12} + \frac{1}{2} \frac{\beta^4}{1 - \beta^4}\right) \frac{1}{\rho_1} \left(\frac{\partial^2 \rho_1}{\partial p_1^2}\right)_s \right] (\Delta p)^2 + O((\Delta p)^3) \end{aligned} \quad (7)$$

Note that each order in Δp in eq. (7) incorporates real-gas effects in an exact way, independent of the form of the equation of state. Eq. (7) and the developments based on it may be the most important results of this paper from a practical point of view. Later in the paper we will also consider briefly the general situation where Δp is large enough that general expressions like eq. (5) apply, by treating integrated versions of the isentropic equation of state.

For the product of compressibility and differential pressure there are the alternative expressions ⁴

$$\frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_s \Delta p = \frac{\Delta p}{\rho c^2} \quad (8)$$

and (using eq.(A-1))

$$\frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_s \Delta p = \left(1 - \frac{p}{Z} \left(\frac{\partial Z}{\partial p} \right)_T \right) \frac{\Delta p}{\gamma p} \quad , \quad Z = \frac{pV}{RT} \quad (9)$$

with

$$\gamma = \frac{c_p}{c_v} \quad , \quad c_{p,v} = c_{p,v}(p,T) \quad (10)$$

Eq. (8), where c is the velocity of sound, relates the compressibility to experimentally measurable quantities. Eq. (9) relates real-gas effects explicitly and exactly to Z factor expressions by equations of state, in a way valid both for orifices, nozzles and venturi tubes:

$$\varepsilon = 1 - \left(\frac{3}{4} + \frac{\beta^4}{1 - \beta^4} \right) \left(1 - \frac{p}{Z} \left(\frac{\partial Z}{\partial p} \right)_T \right) \frac{\Delta p}{\gamma p_1} + \dots \quad (11)$$

The prescribed regulation ⁶ for orifice measurement of fiscal custody transfer of gas specifies $\Delta p < 0.5$ bar. At pressures of order 100 bar and above in orifice measurements, there is then no reason to study more than the lowest order correction in $\Delta p/p_1$.

Our result can now be compared to the standard expression for ε for orifice measurements ¹, the expansion parameter of which including κ (defined by the isentropic equation of state on a polytropic form) instead of γ :

$$\varepsilon^{ISO} = 1 - (0.41 + 0.35 \beta^4) \frac{\Delta p}{\kappa p_1} \quad (12)$$

$$p\rho^{-\kappa} = \text{constant} \quad , \quad \kappa = \kappa(p,T) \quad (13)$$

One objective of this paper will be to demonstrate that κ is a function of both p and T , and that the standard treatment ¹ includes real-gas effects in a way which is unclear at best.

For now we consider briefly the ideal-gas limit, where ⁴

$$\kappa^{\text{IDEAL}} = \gamma_0 = \frac{c_p^*}{c_v^*}, \quad c_{p,v}^* = c_{p,v}^*(T) \quad (14)$$

Eq. (11) with $Z \equiv 1$ and $\gamma = \gamma_0$ should reproduce eq. (12); however, it does not. We will comment on this in the discussion section.

To be able to proceed with the development leading to eqs. (7) and (11), in the next section we will first introduce virial expansion predictions for the isentropic equation of state.

3. THE ISENTROPIC EQUATION OF STATE BY A VIRIAL EXPANSION

The isentropic equation of state is obtained by simultaneous integration of eqs. (A-1) and (A-2). Note that T in eq. (A-1) varies with pressure as given by eq. (A-2). Formally, the result has been expressed in eq. (13). This equation of state receives real-gas contributions from the specific heats as well as from the isothermal derivative in eq. (A-1). It is immediately clear that

$$\kappa \neq \gamma \quad (15)$$

except for the case of an ideal gas.

[Note that we specifically exclude the near-critical region from the range of validity of this approach, and not only because of convergence problems: The equation of state in this region is given by power laws due to universality, which are not reproduced by 'classical' equations of state to which the virial coefficients are often fitted. Universality predictions for the operation of differential pressure meters will be addressed elsewhere ⁷ .]

By eqs. (10), (14), and (A-4) through (A-8), the lowest order real-gas corrections to the specific heat ratio are given by

$$\begin{aligned} \gamma &= \gamma_0 \frac{1 + (c_p^* - c_p^*)/c_p^*}{1 + (c_v^* - c_v^*)/(c_p^* - R)} \\ &= \gamma_0 \left\{ 1 + \frac{1}{c_p^*} \left[-T \frac{\partial^2 B_2}{\partial T^2} p - \frac{1}{RT^2} \left(1 - T \frac{\partial}{\partial T} + \frac{T^2}{2} \frac{\partial^2}{\partial T^2} \right) (B_3 - B_2^2) p^2 + \dots \right] \right. \\ &\quad \left. + \frac{1}{c_p^* - R} \left[\left(T \frac{\partial^2 B_2}{\partial T^2} + 2 \frac{\partial B_2}{\partial T} \right) \left(p - \frac{B_2}{RT} p^2 \right) + \frac{1}{2RT} \left(T \frac{\partial^2 B_3}{\partial T^2} + 2 \frac{\partial B_3}{\partial T} \right) p^2 + \dots \right] \right\} \end{aligned} \quad (16)$$

Similarly, the lowest order corrections in the right-hand-side partial derivatives in eqs. (A-1) and (A-2) are found to be

$$\left(\frac{\partial g}{\partial p}\right)_T = \frac{g}{p} \left\{ 1 - \frac{B_2}{RT} p + \frac{3B_2^2 - 2B_3}{(RT)^2} p^2 + \dots \right\} \quad (17)$$

$$\left(\frac{\partial v}{\partial T}\right)_p = \frac{R}{p} \left\{ 1 + \frac{1}{R} \frac{\partial B_2}{\partial T} p + \frac{T \frac{\partial}{\partial T} - 1}{(RT)^2} (B_3 - B_2^2) p^2 + \dots \right\} \quad (18)$$

Eqs. (A-1) and (A-2) can now be integrated, if we know the temperature dependence of B_2 and B_3 . The equations are coupled in the sense that the temperature's dependence on pressure at constant entropy on the right-hand side of eq. (A-1) is given by eq. (A-2). Note that if we seek only the first order correction to ideality in the isentropic equation of state by incorporating only B_2 in eq. (1), it will suffice to use the ideal-gas version of eq. (A-2) in the integration: Lowest-order corrections in eq. (A-2), if inserted into eq. (A-1), lead to contributions of order $(B_2)^2$, which are of the same order in pressure as the neglected B_3 contributions.

We do not address here the question of radii of convergence for the expansions. However, we assume that low order terms of the pressure-explicit expansion can be used at supercritical temperatures even above the critical pressure to obtain order-of-magnitude estimates of real-gas effects, and in any case to disclose the general form of the corrections. Table 1 shows a numerical example for a model natural gas using a (not completely realistic) cubic equation of state, for which there is fairly fast convergence (possibly of an asymptotic kind) even at 150 bar.

The calculation of real-gas effects in the isentropic equation of state requires an accurate knowledge of the general equation of state, since first and second temperature derivatives of B_2 are required. By induction, even superbly comprehensive³ treatments of the thermodynamics of the flow problem will have a superficial accuracy only, if an inaccurate equation of state serves as a starting point.

4. LOW ORDER ISENTROPIC RELATIONS FROM A CUBIC EQUATION OF STATE

Cubic equations of state⁸ were originally introduced in petroleum technology to facilitate two-phase equilibrium calculations. They are usually two-parameter expressions, which implies that their phenomenological accuracy corresponds to relating the second and third virial coefficients to critical parameters by the principle of corresponding states. The various cubic equations in use⁸ are distinguished by different values of the critical Z factor, Z_c . Cubic equations are often used also at supercritical temperatures even above the critical pressure (as will be done here), although even the best ones lose their high accuracy when the pressure exceeds the critical value⁹.

For explicit predictions by the approach of the previous section, we use the van der Waals equation:

$$p = \frac{RT}{v-b} - \frac{a}{v^2} \quad (19)$$

$$a = \frac{9}{8} RT_c v_c \quad , \quad b = \frac{1}{3} v_c \quad , \quad Z_c = \frac{3}{8} \quad (20,21,22)$$

$$B_2 = b - \frac{a}{RT} \quad , \quad B_3 = b^2 \quad (23,24)$$

i.e.,

$$A_2(T) = \frac{1}{RT} \left(b - \frac{a}{RT} \right) = \frac{1}{8} \left(1 - \frac{27}{8} \frac{T_c}{T} \right) \frac{T_c}{T} \frac{1}{p_c} \quad (25)$$

$$A_3(T) = \frac{a}{(RT)^3} \left(2b - \frac{a}{RT} \right) = \frac{27}{256} \left(1 - \frac{27}{16} \frac{T_c}{T} \right) \left(\frac{T_c}{T} \right)^3 \frac{1}{p_c^2} \quad (26)$$

Behind this particular choice lies the unholy motive of simplicity: Contrary to most other cubic equations, the van der Waals equation leads to rational numbers as coefficients, and its a parameter does not depend on temperature. An eventual loss of accuracy compared to

the results by more refined cubic equations is not thought to be decisive for the lowest order predictions of the present paper, especially when also the gain in clarity is considered.

In Table 1, estimates of A_2 and A_3 are given for a set of parameter values¹⁰ for a model natural gas at a supercritical temperature. If higher orders converged as fast, the A_2 and A_3 terms would give Z with less than 5 % deviation even at 150 bar. Provided, of course, that the expansion can be trusted under these extreme conditions.

For the van der Waals equation, $c_v - c_v^* \equiv 0$, by eqs. (19) and (A-5). In this particular case one can then compute the remaining real-gas corrections in eq. (16) by eq. (A-3), to any order in the virial expansion (which is the reason why eq. (A-3) has been reproduced in this paper).

By eqs. (16), (17), (18), and (20) through (24), one finds for eqs. (A-1) and (A-2), with two orders included in the pressure-explicit form of the virial expansion:

$$\left(\frac{\partial Q}{\partial p}\right)_s = \frac{1}{V_0} \frac{Q}{p} \{1 + C_2(T) p + C_3(T) p^2 + \dots\} \quad (27)$$

$$\left(\frac{\partial T}{\partial p}\right)_s = \frac{R}{c_p^*} \frac{T}{p} \{1 + D_2(T) p + D_3(T) p^2 + \dots\} \quad (28)$$

Integrated along an isentropic path, and neglecting the slow^{4 10} temperature variation of c_p^* and c_v^* :

$$p \varrho^{-\gamma_0} \{1 + E_2(T) p + \dots\} = \text{constant} \quad (29)$$

$$\frac{T_0}{T} = \left(\frac{p_0}{p}\right)^{R/c_p^*} \{1 + O(p/p_c)\} \quad (30)$$

In eq. (30), p_0 and T_0 are ideal-gas reference values. For our purposes it suffices to present the ideal-gas version of the p - T relationship, since only the first order correction has been used in eq. (29). The coefficients are

$$\begin{aligned}
 C_2(T) &= \frac{a}{(RT)^2} \left(1 - 2\frac{R}{c_p^*}\right) - \frac{b}{RT} \\
 &= \left(\frac{27}{64} \left(1 - 2\frac{R}{c_p^*}\right) \frac{T_c}{T} - \frac{1}{8}\right) \frac{T_c}{T} \frac{1}{p_c}
 \end{aligned} \tag{31}$$

$$C_3(T) = -3 A_2(T) C_2(T) - \frac{2}{(RT)^2} \left[b^2 + \frac{R}{c_p^*} a C_2(T) \right] \tag{32}$$

$$D_2(T) = \frac{a}{(RT)^2} \left(1 - 2\frac{R}{c_p^*}\right) \tag{33}$$

$$\begin{aligned}
 D_3(T) &= D_2(T) \left\{ -3 A_2(T) - \frac{\frac{b}{RT} + 2\frac{R}{c_p^*} D_2(T)}{1 - 2\frac{R}{c_p^*}} \right\}
 \end{aligned} \tag{34}$$

$$E_2(T) = \frac{a}{(RT)^2} - \frac{1}{1 - \frac{R}{c_p^*}} \frac{b}{RT} \tag{35}$$

In eq. (35), the dependence on T is understood to be transformed into a dependence on p by insertion from eq. (30). The R/c_p^* factors distinguishing eq. (35) from eq. (31) show that the temperature variation enters the real-gas corrections to the isentropic equation of state in a non-trivial way.

Table 2 shows typical values of the coefficients, calculated with the same set of parameters as in Table 1. A fortuitous cancellation takes place in eq. (31) between real-gas contributions from γ and the other real-gas contributions; with the γ contributions neglected one would get for C_2 the value of A_2 (Table 1) with the opposite sign. Note that this cancellation is a parameter-dependent quirk of Nature for the model natural gas used, which depends also on the choice of equation of state. However, the general form of eq. (31) shows that there will be some degree of cancellation also for other cubic equations of state, which stresses the importance of making a wise choice. (For our particular choice, C_3 contributions are seen to be more important than the C_2 contributions from about 100 bar on.)

Anyway, the importance of taking also the isentropic temperature variation properly into account is clearly demonstrated by Table 2: In eqs. (32) through (35) there is no such strong cancellation.

A comparison of eq. (13) to the combination of eqs. (29) and (35) serves to demonstrate that κ is a function also of pressure, with a considerable variation as the pressure grows from the ideal-gas state to the values of concern to us in this paper.

Eventually in this section, we calculate the isentropic enthalpy per mass unit from eqs. (2), (29) and (30) by once more neglecting the temperature variation of the ideal-gas specific heats:

$$H(p) - H_0 = \frac{\gamma_0}{\gamma_0 - 1} \frac{p}{\rho} \{1 + F_2(T) p + \dots\} \quad (36)$$

$$F_2(T) = \frac{1 - 2\frac{R}{c_p^*}}{2\gamma_0 - 1 - 2\gamma_0\frac{R}{c_p^*}} \frac{a}{(RT)^2} - \frac{1}{2\gamma_0 - 1 - \gamma_0\frac{R}{c_p^*}} \frac{b}{RT} \quad (37)$$

The dependence of T on p at any point along the isentropic path is once more assumed to be given by eq. (30). A numerical estimate of $F_2(T)$ (Table 2) shows considerable cancellations, as in $C_2(T)$. (Notice that R/c_p^* can be expressed by γ_0 , to simplify some coefficients. We have kept the form R/c_p^* to trace the origin of the various terms.)

A more comprehensive approach in the case where $H(p) - H_0$ is not adequately given by the lowest order in $\Delta p/p_1$, would be to include the temperature variation¹⁰ of c_p^* and c_v^* via the pressure in the integrations to obtain eqs. (29) and (36). This would probably necessitate numerical integration. Still, it would be a point to bear in mind in an analysis of the large- Δp case, since this temperature variation would influence the amount of cancellation in eqs. (35) and (37).

In the present paper we will leave the development of the general case at this stage. For the remainder of this presentation we will once again consider the limit of small $\Delta p/p_1$ values.

5. ϵ BY A VIRIAL EXPANSION OF A CUBIC EQUATION AT SMALL Δp

In preceding sections we have found a general expression for the expansibility factor for small $\Delta p/p_1$, as well as an approximation by two virial coefficients for the pressure derivative of the isentropic equation of state. By the results found for the magnitude of A_2 and A_3 (Table 1), we will now apply the combined approach for supercritical temperatures at the pressures of interest, above the critical pressure. We insert eq. (27) into eq. (7) in the limit of small differential pressure:

$$\epsilon = 1 - \left(\frac{3}{4} + \frac{\beta^4}{1 - \beta^4} \right) (1 + C_2(T_1) p_1 + C_3(T_1) p_1^2 + \dots) \frac{\Delta p}{\gamma_0 p_1} + O((\Delta p/p_1)^2) \quad (38)$$

This expression does not lend itself easily to a direct comparison with the fit (12), in which κ is supposed to include all real-gas effects in an unclear way. Our expression (38), on the other hand, separates out real-gas effects in a tidy way, and keeps the clearly defined and parametrized¹⁰ ideal-gas value γ_0 as part of the expansion parameter.

Eqs. (31) and (38) show that for a given temperature, a given differential pressure, and a given critical pressure, the $C_2(T)$ term leads to a constant contribution to ϵ , independent of the total pressure. The magnitude of this contribution is strongly dependent on the equation of state, due to the cancellations in $C_2(T)$. The corresponding contribution to ϵ from the $C_3(T)$ term is proportional to the absolute pressure p_1 , for given values of all other parameters and variables.

By Table 2, the $C_2(T)$ and the $C_3(T)$ terms contribute with opposite signs, for the equation of state and the parameter values considered in this paper. The $C_3(T)$ contribution is even larger than that from $C_2(T)$ in absolute magnitude, for p_1 larger than about 100 bar. This is due to the cancellations in $C_2(T)$, and does not reflect any convergence problems in the virial expansion.

6. DISCUSSION

The low order results have revealed cancellation effects, which delimits the approach's accuracy, but which will be present in disguise also in superficially more sophisticated procedures. The low order approach, including the blessing of a composition-independent formalism, is a convenient way to analyze these effects. In a forthcoming paper¹¹ we will study the equation-specific effects, via predictions by other equations of state for the virial coefficients.

For a subsonic nozzle or a venturi tube, the ISO standard's expression¹ for the expansibility coefficient ϵ is reproduced by the ideal-gas limit of eq. (36) inserted into eq. (5). This holds for any value of the ratio $\Delta p/p_1$. Then, the present standard's formalism cannot include real-gas effects, except in an approximate and non-rigorous way via the variation of κ with pressure. In particular, as was shown by numerical values in Table 2, there are cancellations between real-gas effects in eq. (27), which shows the advice¹ to use γ if κ is not known, to be untenable.

However, the standard's expression for ϵ for orifice plates at small $\Delta p/p_1$ is not reproduced by our exact results even in the ideal-gas limit. What may cause this discrepancy?

Obviously, real-gas effects may be expected at high pressure also in the discharge coefficient C , in the orifice and classical nozzle (as different from the venturi nozzle) cases: The jet cross-section downstream of the mechanical contraction will bounce up again from its minimum value at the vena contracta, which should depend also on non-ideal effects in the compressibility. If we assume that the discrepancy is not simply due to a bad fit, we may thus offer this explanation: The fit (12) may include real-gas effects and more general compressibility effects also from the discharge coefficient C , and possibly also the effects of a permanent pressure fall due to dissipative losses. Concerning contributions of order $(\Delta p/\gamma_0 p_1)^2$, eq. (7) shows that in the ideal-gas limit they would contribute to the β -independent part of the discrepancy between eqs. (12) and (38) with the opposite sign of what is observed.

We would argue that real-gas effects as well as general compressibility effects in ϵ and C should be analyzed separately during the quest for an understanding of the effects. Concerning dissipative losses, it would seem logically most consistent to include any such effects in the discharge coefficient. And for a classical nozzle, one might expect to have the same type of non-ideal effects (thermodynamical as well as hydrodynamical) as for an orifice. Why, then, does the ISO standard ¹ adopt different formalisms for ϵ for orifices and classical nozzles in the limit of small $\Delta p/p_1$?

It follows that improvements of differential pressure metering accuracy for natural gas at high pressure will involve, as a basis, a complete theoretical and phenomenological reanalysis of the various meters. For a consistent treatment of real-gas effects, the polytropic approach should be abandoned, and the formalism of the present paper involving ideal-gas values like γ_0 as well as corrections derivable from (or correlatable by) equations of state should be introduced. As far as possible, a composition-independent formalism should be used. Any real-gas effects in the discharge coefficients should be treated separately from those in the expansibility factors.

A completely new experimental program will be needed for the final correlation of the basic results to metering practice. These experiments should be designed so as to distinguish real-gas effects in C from those in ϵ . Furthermore, they should distinguish clearly effects of dissipative losses from the other types of non-ideal effects.

7. CONCLUSION

The prediction of the real-gas expansibility factor at high pressure provides a decisive test of the reliability of equations of state, since cancellations in low order virial coefficients are involved. Further analyses can be instructively simplified by the low order approach's composition-independent formalism.

In particular, the polytropic approach with the replacement of the isentropic exponent by the specific heat ratio, is a fundamentally inconsistent part of an approach to high accuracy at high pressure.

The exact result for the expansibility factor is in basic disagreement with an ISO standard expression for orifice measurements, in the combined limit of small real gas contributions and small relative differential pressure. An analysis of possible real-gas effects and compressibility effects in general in the discharge coefficient, should enter future analyses of this discrepancy.

New calibration experiments, designed to distinguish between real gas compressibility effects in the expansibility factor and in the discharge coefficient, as well as dissipative effects, will be needed in the final correlation of this new and systematic approach to actual metering practice at high pressure.

ACKNOWLEDGEMENT

The author would like to thank S.K. Andersen for pointing out a mistake in the draft of this paper, and H. Norvik for clarifying discussions of cubic equations of state.

APPENDIX: STANDARD THERMODYNAMICAL RESULTS

We denote molar values for intensive variables by small letters. The three basic thermodynamical relations to be used are ^{4 8}

$$\left(\frac{\partial g}{\partial p}\right)_s = \frac{c_v}{c_p} \left(\frac{\partial g}{\partial p}\right)_T \quad (\text{A-1})$$

$$\left(\frac{\partial T}{\partial p}\right)_s = \frac{T}{c_p} \left(\frac{\partial v}{\partial T}\right)_p, \quad \rho v = M \quad (\text{A-2})$$

$$c_p - c_v = - \frac{T \left(\frac{\partial p}{\partial T}\right)_v^2}{\left(\frac{\partial v}{\partial p}\right)_T} \quad (\text{A-3})$$

The deviation of c_p and c_v from the ideal-gas values c_p^* and c_v^* is given by ⁷

$$c_p - c_p^* = - \int_0^p T \left(\frac{\partial^2 v}{\partial T^2}\right)_p dp \quad (\text{A-4})$$

$$c_v - c_v^* = \int_{-\infty}^v T \left(\frac{\partial^2 p}{\partial T^2}\right)_v dv \quad (\text{A-5})$$

The paper uses virial coefficients from the volume-explicit as well as the pressure-explicit version of the virial equation of state:

$$\frac{pv}{RT} = 1 + \frac{B_2}{v} + \frac{B_3}{v^2} + \dots, \quad B_i = B_i(T) \quad (\text{A-6})$$

$$= 1 + A_2 p + A_3 p^2 + \dots$$

$$A_2 = B_2/RT \quad (\text{A-7})$$

$$A_3 = (B_3 - B_2^2)/(RT)^2 \quad (\text{A-8})$$

NOMENCLATURE

a	Coefficient in the van der Waals' equation of state
A_2, A_3	Virial coefficients, pressure-explicit representation (A_2 also used for contraction area)
b	Coefficient in the van der Waals' equation of state
B_2, B_3	Virial coefficients
c	Velocity of sound
c_p, c_p^*	Molar specific heat at constant pressure, * for ideal gas
c_v, c_v^*	Molar specific heat at constant volume, * for ideal gas
C	Discharge coefficient
C_2, C_3	Coefficients in $(\partial q/\partial p)_s$
D_2, D_3	Coefficients in $(\partial T/\partial p)_s$
E_2	Coefficient in isentropic equation of state
F_2	Coefficient in isentropic enthalpy per mass unit
H, H_0	Isentropic enthalpy per mass unit, 0 denoting indefinite additive contribution
IDEAL	(As superscript) ideal gas value
ISO	(As superscript) ISO standard value
\dot{m}	Mass flow rate
M	Molar mass
O	Order
p, p_c	Pressure (also int. variable), c for critical value
p_0	Reference pressure
p_1, p_2	Pressure, indices denoting locations
R	Molar gas constant
s	Molar entropy
T, T_0, T_c	Temperature, 0 and c for reference and critical values
u_1, u_2	Flow velocity, indices denoting locations
v	Molar volume
Z, Z_c	Gas deviation factor, c for value at critical point
β	Diameter ratio
Δ	Difference operator
ϵ	Expansibility factor
γ, γ_0	Specific heat ratio, 0 for ideal gas value
κ	Isentropic (polytropic) exponent
ρ, ρ_1, ρ_2	Density, indices denoting locations

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TABLES

97 mole% C1, 3 mole% C2	
$T_c = 194.1 \text{ K}$	$p_c = 46.1 \text{ bar}$
At $T = 273.15 \text{ K}$:	
$\frac{c_p^*}{R} = 4.16$	$\gamma_0 = 1.316$
$A_2 = -1/(371 \text{ bar})$	$A_3 = -1/(532 \text{ bar})^2$

Table 1: Numerical example for given composition and temperature, assuming a van der Waals gas

$C_2 = 1/(2120 \text{ bar})$	$C_3 = -1/(463 \text{ bar})^2$
$D_2 = 1/(417 \text{ bar})$	$D_3 = 1/(441 \text{ bar})^2$
$E_2 = 1/(480 \text{ bar})$	
$F_2 = 1/(1070 \text{ bar})$	

Table 2: Coefficients in expressions leading to isentropic equation of state and isentropic enthalpy, parameters as in Table 1

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COMPARISON OF SAMPLING METHODS BY WATER INJECTION

4.1

Lecturer: Section Leader N. W. King,
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COMPARISON OF SAMPLING METHODS BY WATER INJECTION

by

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SUMMARY

At present the only recognised method of comparing or calibrating water-in-oil sampling systems is to measure their response to a known quantity of water injected into the oil flow. This paper explains the basics of water injection and goes on to describe some of the laboratory and field experience of the NEL Automatic Sampling project in its study of sampling devices and methods.

1 INTRODUCTION

Many sampling devices and methods are currently available for the determination of the water content of crude oils. Although the results they produce are often used for fiscal and custody transfer calculations there is no recognised means of calibrating a sampler such as is employed, for instance, in calibrating a flowmeter. Whereas the quantity of oil transferred can be measured to within small and known uncertainties, the quality of the oil is established to perhaps a lesser degree. The problem of water content measurement is admittedly a complicated one, involving many factors; variations in homogeneity both spatially and temporally in the pipe from which the sample is taken, isolation and collection of the sample, storage of the sample and then the chemical analysis. The most popular, and essentially the only, method of checking the performance of a sampling system is to subject it to a known water content by water injection as described in section 15 of reference 1 and section 7 of reference 2.

The NEL Automatic Sampling Project, which is sponsored by a consortium of sixteen oil concerns, has a remit to study and improve automatic water-in-oil sampling devices and methods. Some of the techniques and findings of the project are given in references. 2 to 8. The project has relied heavily on water injection techniques in both laboratory test facilities and in field installations. The following sections describe the ways in which water injection was effected in both cases and how successful those methods were. Because the work was commercially funded, however, only selected general findings can be presented in this paper.

2 PRINCIPLES OF WATER INJECTION

Proving a sampling system by water injection involves producing a known water content by injecting a metered supply of water into a metered flowrate of oil and adding it to the existing background water content. In principle it would seem that the water content derived from the sampling system need only be compared to the known water content in order to ascertain the performance of the sampling system. In practice it is far from being so straightforward; what about the homogeneity of the injected water in the oil? what is the water droplet size? what is the background water content and did it vary during the test? These, and a host of other problems, complicate the method.

2.1 Water Injection Requirements

References 1 and 2 specify the equipment and the arrangement that should be employed in water injection tests. These are:

- (a) Suitable connection valves, strainer, pressure gauges, and piping.
- (b) A flowmeter capable of measuring the injected volume of water during a test with an uncertainty of less than ± 2 per cent.
- (c) A flowmeter capable of measuring the volume of oil flowing during a test also with an uncertainty less than ± 2 per cent.

(d) Location of the water injection point as far upstream of the sampling point as possible so that the water will traverse all the pipe fittings etc expected to produce the required degree of mixing.

(e) The water injection flow rates should be between 1.0 per cent and 5.0 per cent of the crude oil flow during the test. Note, however, that if for operational reasons the water injection flow rates have to be less than 1 per cent then the measurement of injected water quantity and the accuracy of the laboratory analytical procedure become critical in the assessment of the sampling performance.

(f) The water injection point should be at the bottom or the side of the crude carrying pipe line and the velocity of injection should not exceed 130 per cent of the crude pipe line velocity.

2.2 Testing Procedure

Having installed and checked all the equipment as indicated above the following procedure should be adopted in the proving tests:

(a) Select a time when the pipeline conditions can be held steady.

(b) Arrange to conduct the test at the worst conditions expected during normal use of the sampling system, ie using an oil with the lowest viscosity and the lowest density from the normal range of oils used. Adjust the oil flowrate to the minimum pipeline velocity normally encountered.

(c) Once stable conditions are obtained and the sampler system has been purged, operate the sampler for at least one hour to obtain the 'before' baseline water content of the oil.

(d) Start water injection as described above and continue for at least one hour. After allowing time for the lag between water injection and arrival at the sampling point, begin to take the 'with water injection' sample. Note that at low flow rates the injected water may move at a slower velocity than the crude oil and sampling into the test receiver should therefore be continued for some time after the end of the expected passing of the dry oil.

(e) After ceasing to inject water, continue to sample for a further hour to obtain the 'after' baseline water content. The difference between the 'before' and 'after' baseline water contents should not exceed 0.1 per cent.

(f) In all the 'before', 'with water injection' and 'after' sampling, normal procedures for sample handling, mixing and analysis should be performed.

2.3 Calculations

The deviation between the average water content in the test sample minus the baseline water content, and the average water injected should be calculated from the following formulae:-

$$W_{dev} = (W_{test} - W_{base}) - W_{inj}$$

where:

W_{dev} is the deviation of the percentage water in the samples from the average injected water.

W_{test} is the percentage of water in the test sample.

W_{base} is the average percentage of water in the baseline sample before and after the test.

W_{inj} is the percentage of water injected into the oil and:

$$= \frac{W}{V} \times 100$$

W is the total volume of the injected water (cubic metres)

V is the total volume of the oil and water that passes the sample point during the period when the sampler is in operation collecting the 'with water' sample (cubic metres).

2.4 Ratings for Sampler Performance

References 1 and 2 describe how a measure of a sampler's performance can be obtained by evaluating

$\frac{W_{dev}}{W_{inj}}$ within one of four ratings:

- | | | |
|---|--------------|------------------------------------|
| A | less than | +/- 0.05 |
| B | greater than | +/- 0.05
but less than +/- 0.10 |
| C | greater than | +/- 0.10
but less than +/- 0.15 |
| D | greater than | +/- 0.15 |

Note that these ratings only apply to injected water concentrations of 1 per cent or more. Also note that the value of W_{base} as a percentage of V changes when the water is injected. However, if W_{base} is less than 0.1 per cent the rating W_{dev} changes by less than $0.001 W_{inj}$.

Sampling systems with a Rating A meet the highest requirements, but Ratings of B, C, or D denote a lower performance and consideration should be given to implementing possible improvements in the sampling system.

3 THE NEL LABORATORY TEST FACILITY

At first glance it may seem easier to conduct water injection tests in a laboratory facility than in the field; costs are reduced, there is better control and repeatability of the variables, there is the potential for improved quantitative measurements and transparent pipework can make even qualitative assessments a possibility. However, all is not that simple. For safety and convenience reasons, crude oil cannot be used in the laboratory. Hence, to reproduce the Reynolds and Weber numbers of north sea crudes (2 to 30 cSt viscosity, 0.1 to 1.2 m diameter pipes, 1 to 4 m/s velocity) in a 200 mm diameter laboratory a lighter, 2 cSt kerosine type oil must be used. This means it is easy to separate the water from the kerosine after use, but makes it difficult to produce an homogeneous mixture of water and kerosine at the point of sampling. Much development went into the design of the NEL sampling facility water injection section to overcome this problem.

3.1 Description of the NEL facility

A schematic of the NEL test facility is shown in fig. 1 and a full description given in references 3 and 4. In normal operation kerosine is pumped around the circuit by a variable speed pump capable of 50 l/s flowrate and imparting an energy rise of 220 J/kg. After a long straight 100 mm section the flow passes through a calibrated turbine flowmeter before doubling back on itself and entering a diffuser section into the 200 mm diameter test section. Fig. 2 is a schematic of one of several configurations of the test section which is basically a modular perspex block construction incorporating various elements. A gantry is available so that the test section can be mounted vertically for upward or downward flows tests.

The sampler to be studied can be installed in one of the perspex blocks and positioned any distance downstream of the mixing section and in any orientation. A water micro-injector can be lowered into the flow immediately upstream of the sampler to study the trajectories of the individual water droplets by photographic means. Alternatively, a sampling scoop tube can be inserted in the test section to collect and divert flow into a by-pass loop. A range of small pumps and connection configurations are available for the study of external or by-pass cell samplers.

The water/kerosine mixture in the main flow is then conveyed via a flexible hose into an inlet ring at the bottom of the vertical cylindrical separation tank of 10 m³ capacity. The whorls of small holes on the inlet ring ensure a uniform percolation of the flow into the tank where it rises slowly upwards, allowing the largest water droplets to settle downwards for collection and transfer to settling tanks before re-injection. The oil is collected from the top of the tank and returned via a flexible hose to the main circuit and the pump inlet. The height of the inlet and outlet in the main separation tank can be adjusted to cater for different levels of fluid and also to achieve the best water separation characteristics. If required, a coalescer filter can be brought into the circuit to 'polish' the kerosine and remove any fine water droplets before recirculating to the test section.

It is interesting to note that the test facility can also be run without water injection in a closed loop mode. In this case the separation tank and the coalescer filter are shut off and a measured mixture of water and kerosine constantly recirculated in the loop. The volume abstracted by the sampler is made up by a small feed tank and the small change in water concentration calculated accordingly.

As mentioned above, one of the most difficult parts in the design and operation of the facility was the water injection system. Only after extensive research was the final arrangement decided. Water, from a calibrated metered supply, is injected into the kerosine flow through a water injection section shown as shown in fig. 3. The five nozzles, their jets, feed pipes and annular water gallery are all designed to ensure each nozzle delivers equal water flows into equal cross-sectional areas of the test section. Immediately downstream of the injection section a twin plate arrangement with holes of variable area is installed as shown in fig. 4. Each of the two plates has five square orifices. A cam system is used to slide the plates relative to each other in such a way that the overlap of their orifices produces a square orifice in front of each of the five water injection nozzles. Operation of the cam controls the size of each orifice and the smaller the orifice the faster the water and kerosine mixture flows through and the smaller the water droplets produced. In this way, water droplets of a given and repeatable size can be produced. Immediately downstream of the twin plate arrangement a system of baffle plates is mounted to destroy any jets from the orifices.

Before any samplers were assessed in the facility, tests were conducted to check the quality of the water mixture produced. Firstly a NEL design of sampling scoop tube (see reference 4) was traversed across the vertical diameter of the test section to measure the limits of flow velocities and droplet sizes that could maintain an homogeneous mixture at the sampler position. Secondly, the same scoop tube was used to divert a portion of the main flow through a special droplet sizing section as shown in fig. 5. Short duration flash photography was used to 'freeze' the motion and give photographs from which droplet sizes could be measured.

3.2 Testing procedure and Calculations

The normal practice in performing a test is to mount a given sampler in its desired position and orientation and set the oil flowrate by adjustment of the pump speed and setting the sampling pump speed to give the required sampling rate. After allowing time to purge all the sampling system with neat oil, the water injection pump is started and sufficient time allowed to establish stable conditions before samples are collected for analysis.

Because the laboratory facility is mainly used to study the operation of samplers and the sampling system, tests are usually shorter than the one hour recommended in references 1 and 2. For this, and operational reasons, the tests conducted in the laboratory facility are conducted on a volumetric flowrate basis and not on a total volume basis as described in references 1 and 2. W_{inj} is determined directly from the injected water and kerosine flowmeters as:

$$W_{inj} = \frac{\text{Volumetric flowrate of injected Water}}{\text{Volumetric flowrate of injected water and kerosine}} \times 100$$

This is usually calculated to +/- 0.01 per cent volume for volume (v/v) water.

Because the water is injected into water-free kerosine, $W_{base} = 0$.

W_{test} , the percentage of water in the sample is determined by gravimetric separation of the water and oil components and individual volume measurement in calibrated measuring cylinders or pipettes as below:

$$W_{test} = \frac{\text{Volume of Water in sample}}{\text{Volume of Water \& kerosine in sample}} \times 100$$

This can usually be calculated to better than +/- 0.1 per cent v/v water.

4 THE FIELD TEST FACILITY

The limitations on oil type and pipeline size of a laboratory facility can largely only be overcome by conducting water injection tests in a field installation. An opportunity for such field testing arose when one of the sponsors of the NEL sampling project made available a sampling installation in a refinery. This provided the means to conduct many water injection tests to compare samplers and sampling methods and to study water mixing and water transient behaviour.

4.1 Description of the Field Facility

The field sampling station was located in a refinery at a point where pipe lines running from jetties to the refinery manifolded with headers from a tank farm. In such a location samples could be obtained from tank to tank transfers utilising the tank farm pumps either directly in and out of the jetty head crossover or via the long jetty lines. The sampling station could also be used for sampling from cargoes transferred from ship to shore via the ship's pumps though this was not the best position for such work because of the distance between ship and sampling point. A schematic of the pipe configuration, water injection points and sampling equipment used at the jetty head cross-over during the course of the NEL tests is given in fig. 6.

The sampling station itself was situated on the No. 1 Header about 2 m downstream of the jetty/header manifold. The internal diameter of the mainline pipe at the sampling station was 1.197 m giving a cross sectional area of 1.125 m². The approximate hold up volume between injection and sampling points on the direct route down the no. 2 header, crossover via the no. 3 line and up the no. 1 header was calculated as 37 m³. Hold up between injection and sampling points via the no. 2 header, down the no. 3 jetty line, crossover at the jetty end, return by the no. 2 jetty line and up the no. 1 header was calculated as as 379 m³.

In the NEL tests two 50 mm (2") water injection points were hot tapped onto the no. 2 header as shown in the figure. Although not strictly in accordance with the recommendations of references 1 and 2, the use of two tappings instead of one was necessitated by the use of the fire main as a source of water. Sea water from the refinery fire ring main was piped to each injection point by a 50 mm (2") fire hose via a non-return valve and a ball valve mounted on the pipe. Both injection point hot taps were trepanned to a nominal 50 mm (2") diameter inlet hole.

It can be seen from fig. 6 that the sampling station had provision to mount an in-the-line sampler directly in the pipe wall, and also to mount an external cell sampler in a by-pass loop supplied from a NEL design of scoop tube inserted into the main line. The by-pass loop also had a water-in-oil monitor working on the capacitance principle which was used to monitor the passage of water transients through the sampling station.

The sampling station was provided with a multi-point profiling probe as described in section 6 of reference 1. Profiling tests were conducted before each water injection test and it was found that in all cases the vertical water concentration profile was well within the limits specified in reference 1.

All instrumentation, computers, data loggers, water analysis equipment etc. was housed in a 'Portacabin' adjacent the sampling station. A Commodore PET computer monitored all 4 flowmeters and the Capacitance cell output and recorded them on disc and gave a hard copy both as a print-out and on a chart recorder. During some of the tests the output from the capacitance cell was logged digitally on an Epson PX8 portable computer using the program DATALOG and analysed using the program DATACAL for use in water transient computer simulations described in references 6 and 7.

4.2 Testing Procedure and Calculations

Because of the pipeline size and the quantity of oil concerned, it would have been expensive to measure flowrate using a full bore flowmeter. Total oil transferred during a test was therefore calculated by reading the exporting and receiving tank dip gauges before and after the test and an insertion flowmeter was used to check for any variation of flow during the test. This arrangement had the capability to measure flow to within +/- 2.0 per cent of full flow.

50 mm (2") calibrated turbine flowmeters, together with the requisite upstream and downstream lengths of straight steel pipe, were fitted to each of the seawater lines. The flowmeters were found to correspond with each other when placed in series in the same line at the start and the end of the testing programme. This measurement system had the ability to measure injected flow to +/- 1.0 per cent of full flow.

Several samples were taken both from the by-pass loop and from the centre probe of the profiler before and after water injection to measure the 'before' and 'after' background water contents. All of the NEL tests were conducted on tank to tank transfers and constant background water was obtained either by allowing the tank contents to stand for a long time or by running the tank stirrers for a time before the transfer began.

5 COMPARISON OF WATER INJECTION METHODS

The laboratory and field water injection tests conducted by NEL were directed more to studying sampling instruments and methods rather than proving a particular sampling installation as described and recommended in reference 1. A salient difference between the NEL tests and the recommendations of reference 1 was the shortness of the NEL tests, none of which approached the one hour recommended in reference 1, but this has not affected the validity of the conclusions drawn from these specially designed tests.

5.1 Laboratory Tests

The NEL experience has shown that a laboratory sampling facility can be used to produce repeatable and accurately known flowrates, water contents and droplet sizes for the study and testing of sampling devices and methods. The provision of visual access and high speed photography has proved a useful qualitative tool to assist the studies. The laboratory provides a clean, stable, and controlled working environment in which to conduct test work. It also provides the cheapest, most adaptable and quickest means of performing this work. It is generally accepted that the low viscosity of the kerosine used in the NEL tests and the resulting rapid drop-out of water, gives rise to the most onerous sampling conditions, ie that if a sampler system is shown to work in the laboratory then it is more than likely that it will also work in a field installation.

5.2 Field Tests

Although the laboratory facility has provided a valuable and extensively used tool during the NEL Sampling Project it had several limitations. The most obvious of these were the maximum test section pressure of two or three bar, a maximum working temperature of 40°C and the restriction to a kerosine type oil. It was only by moving to a field installation that these shortcomings could be overcome.

Further, the very strengths of a laboratory facility can also prove to be weaknesses when designing devices and methods for use in a refinery or production platform environments. Operators sitting in the warmth and cleanliness of a cosy laboratory easily forget that the sampling system under test is destined for use in harsher conditions. The laboratory does not experience 150 km/hr winds laced with salt spray or freezing or skin blistering temperatures and spanners with 4m long extensions are never used on the instruments. Only the occasional fleck of rust will make a single circuit of the laboratory facility compared with the sand, straw, rags and wax precipitates found in the field. It is no use designing a system that works perfectly in the laboratory if it does not take these factors into consideration.

On the other side of the coin, however, is the fact that no red faced operations manager will ever enter the laboratory demanding that the test you have just taken three days to set up will have to be postponed indefinitely because someone somewhere has altered shipping times or pipeline export quotas.

5.3 Recommended Water Injection Procedures

The sampler proving procedures outlined in references 1 and 2 work well in a laboratory environment, but can prove difficult in a field application. The recommended one hour duration of water injection is designed to produce a reasonably large sample on which to conduct water content analysis. However, the problem of maintaining a uniform flow and constant background water over that period can be difficult to ensure.

It is also of interest to note that when the recommended uncertainties of ± 2 per cent in water and oil flow and the minimum shift of 0.1 per cent v/v water in background water content are taken into consideration, then the uncertainty in measuring the rating is of the same order as the ± 0.05 for the class A rating.

6 CONCLUSIONS

The experience of the NEL Sampling Project with water injection has shown that:

(1) Water injection in a laboratory test facility can be a cheap, adaptable and accurate tool in the study and evaluation of sampling devices and methods. The use of low viscosity kerosine most likely gives a 'worst case' situation for sampling, but;

(2) A sampling device or method developed in the laboratory facility should always be proved in a field installation by water injection techniques to evaluate the problems of high pressure, temperature and dirty and viscous crudes that cannot be simulated in the laboratory.

(3) The recommendations described in DIS 3171 can be difficult to obtain in the field, particularly those of length of test, measurement of oil flowrates and constancy of background water.

(4) The DIS 3171 recommended uncertainties in oil and water measurement and limits on the constancy of background water can give rise to an uncertainty in the measurement of the rating of the same magnitude as the 'A' rating. Hence, if a valid 'A' rating is to be given to a system, then the uncertainties in the associated measurements must be less than those recommended in the DIS.

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LIST OF FIGURES

- 1 The NEL 200mm Laboratory Test Facility
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- 4 Variable Area Orifice Plate
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- 6 Schematic of Field Sampling Station

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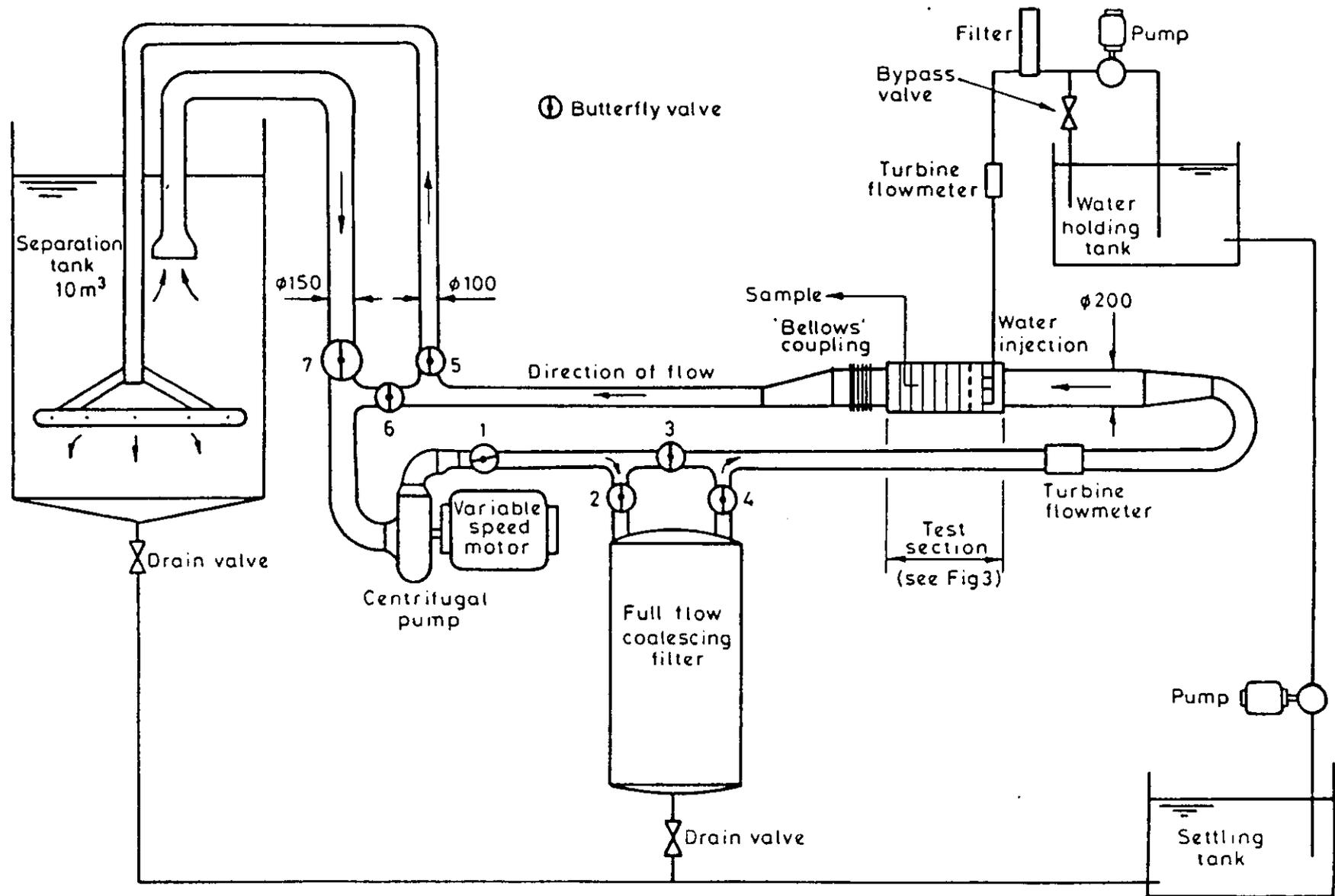


Fig 1 The NEL 200mm Laboratory Test Facility

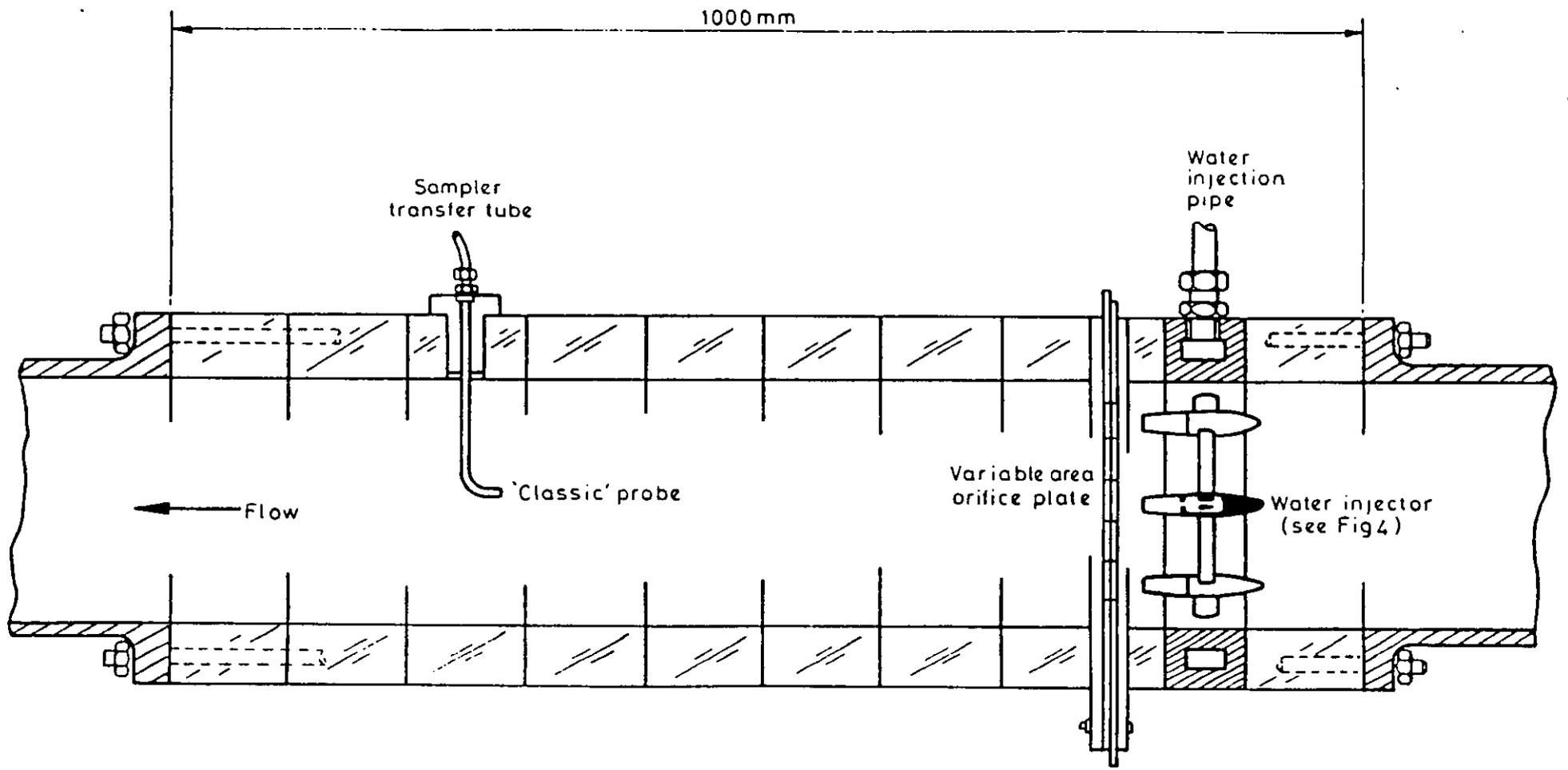


Fig 2 The 200mm Test Section

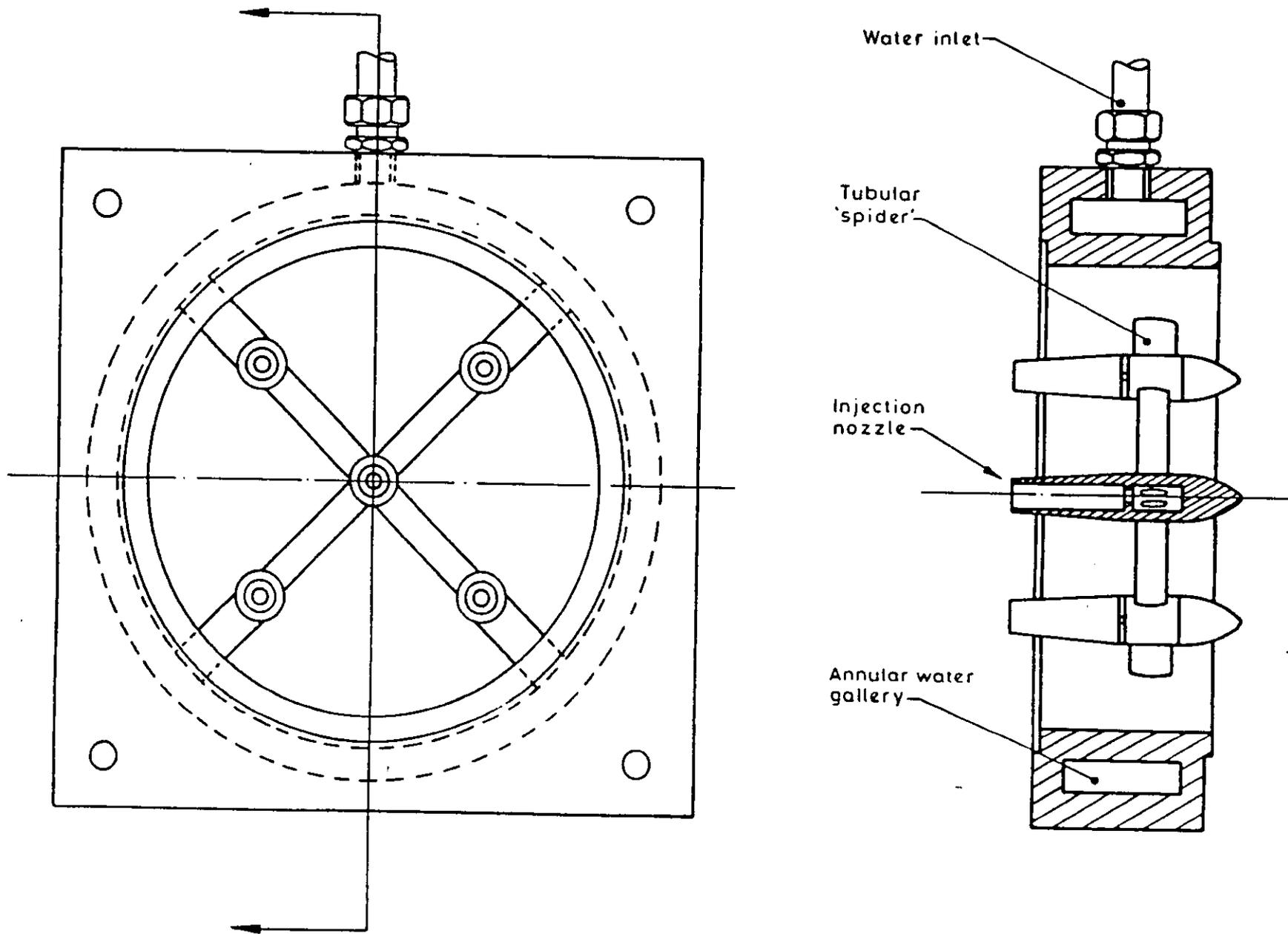


Fig 3 Water Injection Section

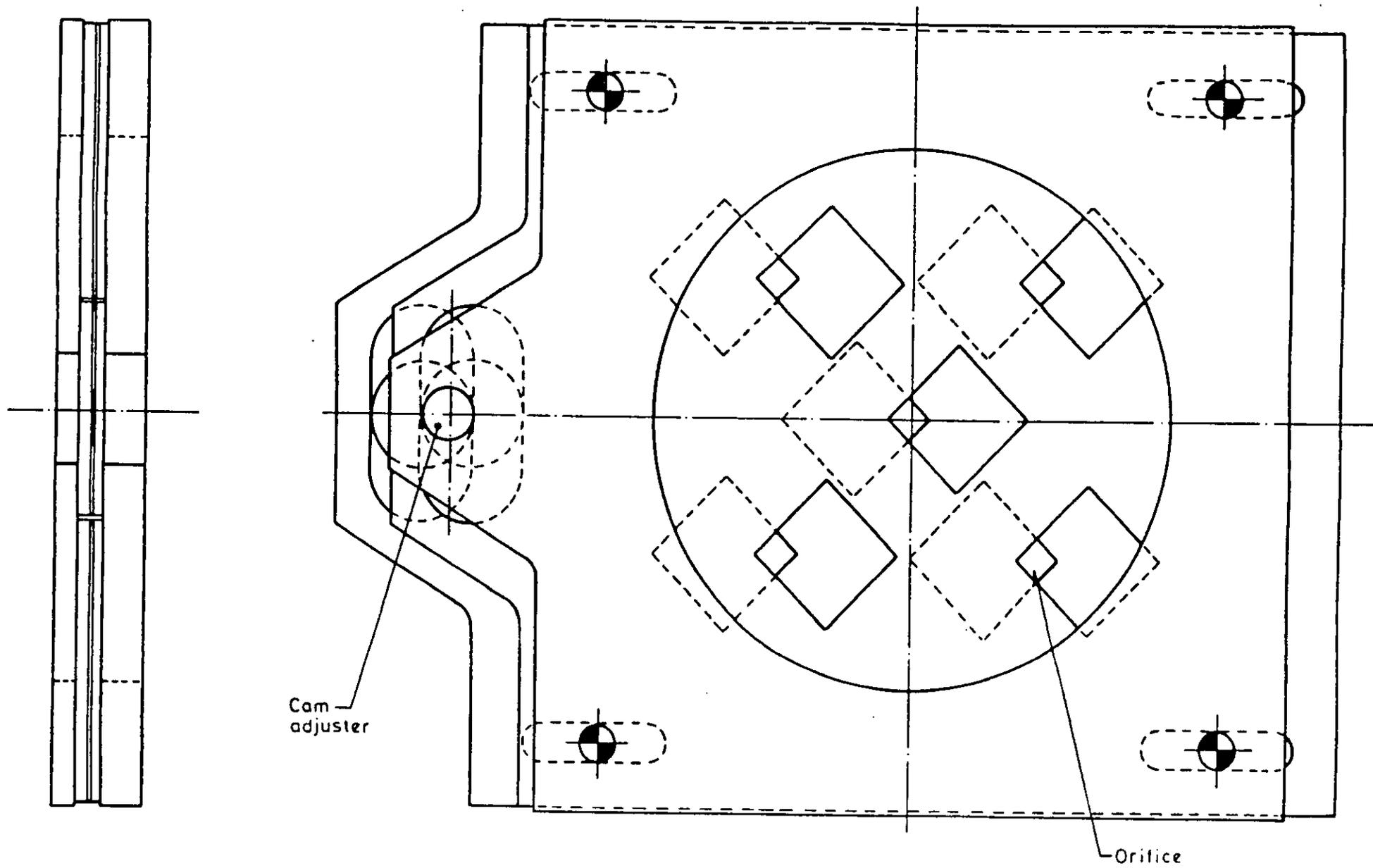


Fig 4 Variable Area Orifice Plate

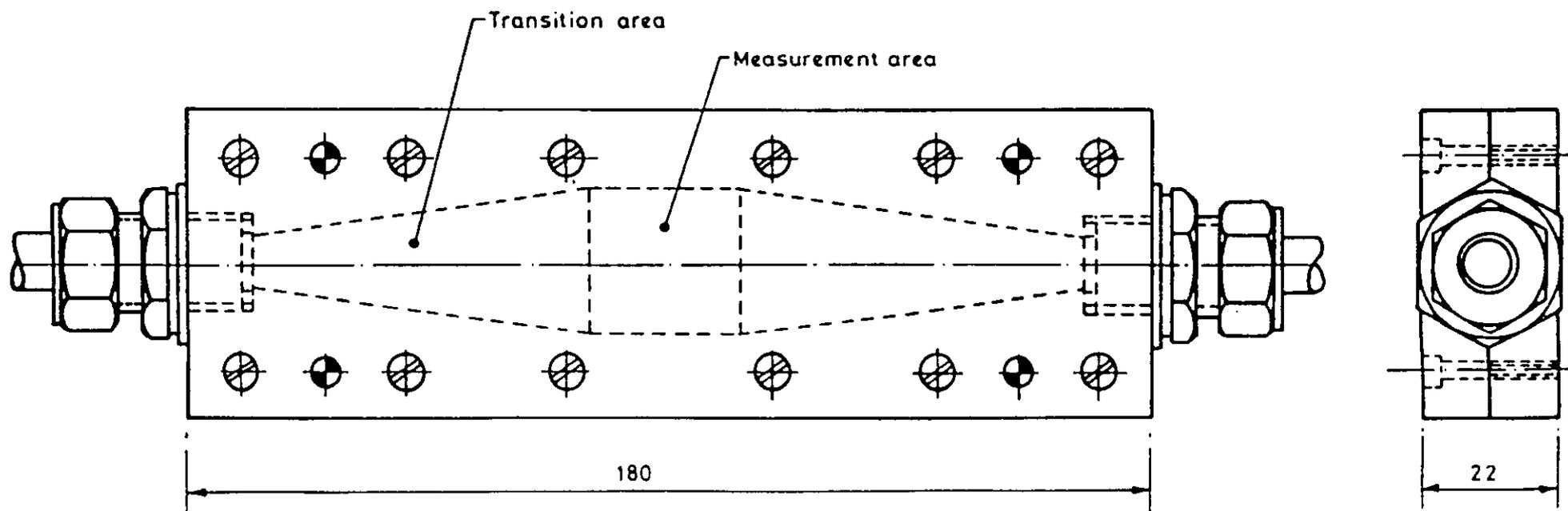
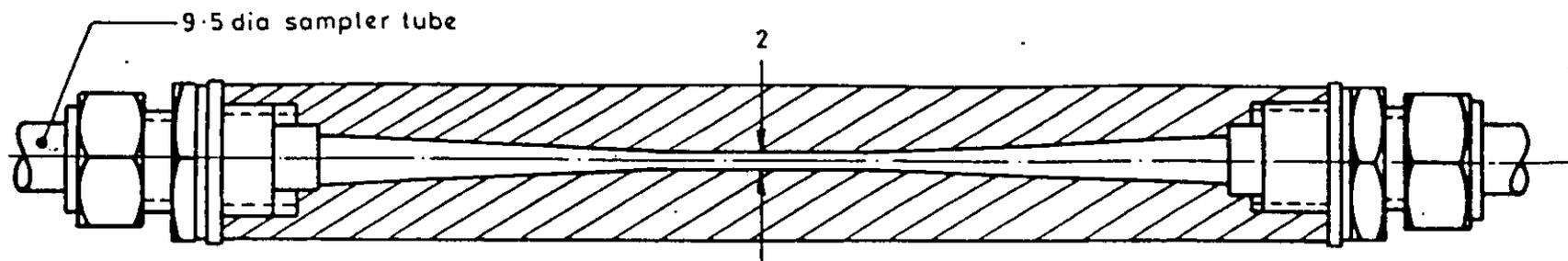


Fig 5 Droplet Sizing Section

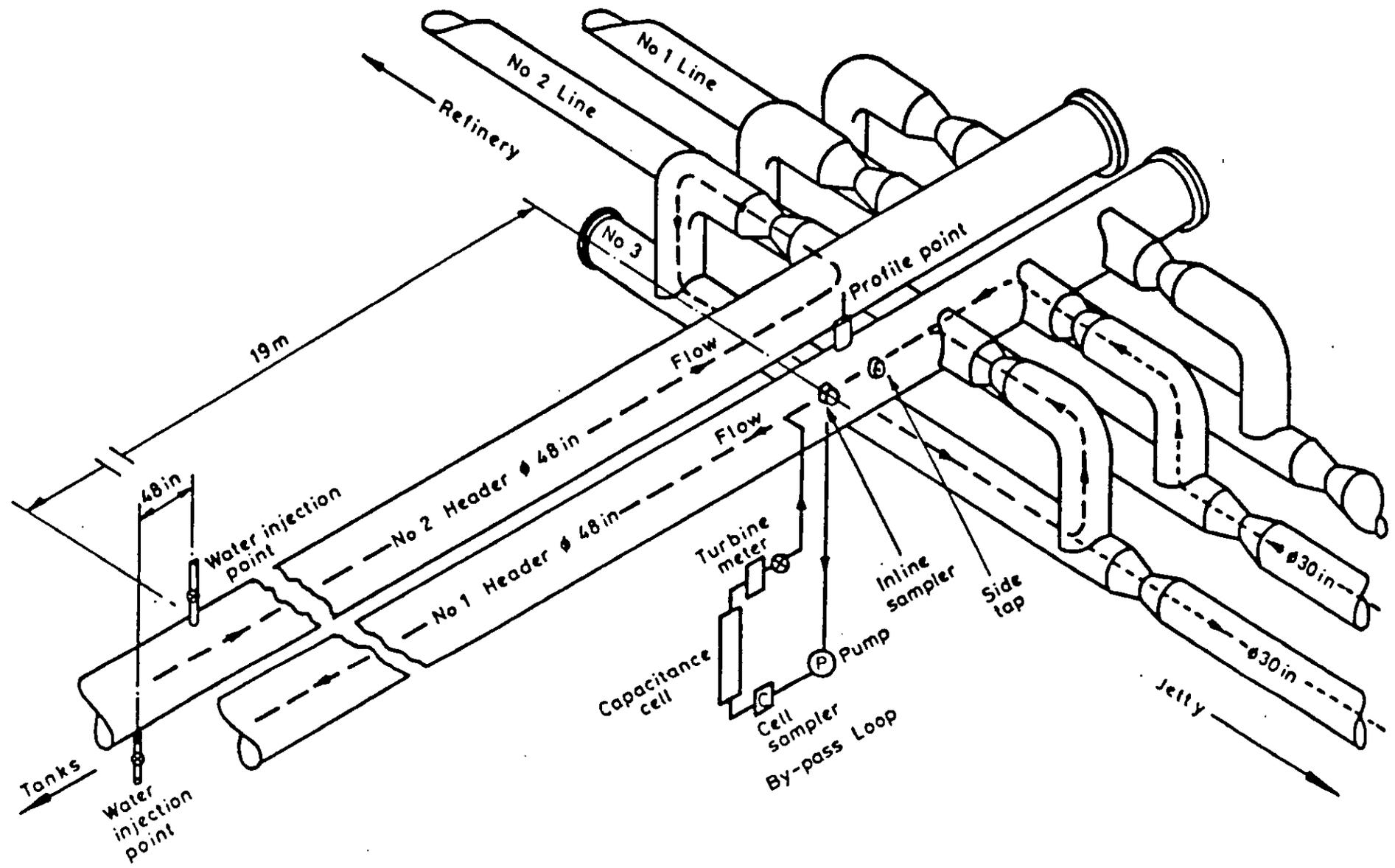


Fig 6 Schematic of Field Sampling Station

**NORTH SEA FLOW METERING
WORKSHOP**

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Stavanger Forum, Stavanger

A SUMMARY OF METHODS ON CALCULATIONS OF GAS
DENSITY

4.2

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A SUMMARY OF METHODS ON CALCULATIONS OF
GAS DENSITY

BY

T.COUSINS and P. MASON.

(1.0) INTRODUCTION

The objective of this paper is to review some of the current methods of calculating density to achieve mass flow measurement. Most flow-meters used for gas measurement, orifice plates, turbine meters, vortex meters etc., measure ACTUAL VOLUMETRIC FLOW, or more specifically ACTUAL FLOW VELOCITY. The value of product is in its Mass as this is an 'inviolable' quantity whereas actual volume flow is different for different conditions such as pressure and temperature. Density must therefore be measured to be combined with the actual volume flow to give mass flow.

There are four methods of obtaining density for gas :-

- a) A fixed estimated value (commonly used in compressed air, steam systems and gas supply to consumers)
- b) Simple checking, by taking a sample of the process fluid and measuring its properties in the laboratory.
- c) On line densitometry, mainly vibrating spool densimeters or gas chromatography.
- d) Calculation of density by pressure and temperature inputs.

The purpose of this paper is to concentrate on the pressure and temperature method of density measurement with emphasis on summarising the methods of correcting for compressibility.

(2.0) REVIEW OF OTHER METHODS

Before discussing the p-T method it is worth reviewing the other methods as it is sensible practice to use two (or more) methods of density determination as a check. Particularly as polling 2 from 3 in fiscal measurement will add greatly to the confidence of the density measured.

(2.1) FIXED ESTIMATED VALUE

Obviously with varying pressures and temperatures such a method will be inaccurate; although it is useful for 'fallback values' and alarm limits. Further if temperature and pressure are reasonably constant it is a useful check for other methods. It is interesting to note that gas is metered uncorrected to households, taking an average annual temperature and an assumed regulated pressure for density calculation. While individually the financial value is small, the percentage loss to the consumer is the same as the gas producers if they used the same method (in the U.K., in an average year British Gas are between 3 and 5% safe in their predictions)

(2.2) SAMPLE CHECKING

For this method samples of the gas have to be removed from the pipeline and taken to the laboratory for analysis. This can be done in a variety of ways, such as the buoyancy gas balance, recording gravitometer, momentum gravitometer etc. The problems with this method are ensuring the test conditions are the same as the flowing conditions (if not they will have to be related back by calculation with consequent errors), how representative is the sample and finally it does not represent a continuous measurement. It is however a very useful comparison for the on-line density and p-T method.

(2.2) ON LINE DENSITOMETRY

There are several methods for on line densitometry, the vibrating spool/plates method and gas chromatography being the most common. A typical vibrating spool densitometer is shown in FIG 1. The spool is set in vibration at resonance in a circumferential mode. Gas passes around the spool changing the mass at the surface, which in turn effects the resonant frequency (f) in the form:-

$$f = \sqrt{K / (M_s + M_g)}$$

Where K is the spring rate, M_s is the spool mass and M_g the local mass of gas. Obviously for maximum sensitivity the mass of the spool must be as low as possible compared to the gas mass. The obvious advantages of the system are direct measurement of density, to in many cases a very high order of uncertainty (better than 0.3%)

There are a number of disadvantages to densitometers:-

- 1) It is difficult of ensure that the sample passing through the densitometer is representative of the fluid passing through the meter. This is alleviated somewhat by different methods of positioning the densitometer.
 - 2) Reliability of the densitometer due to fouling (with the problem of being unable to tell when errors occur)
 - 3) Uncertainty of Velocity of sound correction of certain gases.
- On line Gas chromatography also can be used to give good answers of density however it suffers the problems of:-

- a) Varying density product will give errors (if faster than sample time)
- b) Cost of the instrument.
- c) Lack of ruggedness.

Both methods can give answers better than p-T methods but because of the problems can be considered suspect on their own. A sensible approach would seem to use either or both in conjunction with the p-T methods to be described in Section 5. -

(3.0) DENSITY REQUIREMENTS

As previously stated density is required to obtain mass flow as most flowmeters are volumetric.

The basic flow equations to be satisfied are:

$$\text{ORIFICE PLATE: } \dot{m} = K\sqrt{\Delta P \times e}$$

$$\text{TURBINE/VORTEX: } \dot{m} = KFe$$

A point worth noting is that errors in density measurement for an orifice plate are halved when flow is measured. The positions of measurement of pressure and temperature are usually downstream of the orifice and then corrected back to the orifice conditions. Fig 2. Measuring pressure at the downstream is useful as the jet mixes together any stratified gas, to give a better density distribution. It is also important obviously that the temperature is related to that at the orifice. Recent work seems to show that significant temperature differences are seen at the orifice due to the fluid mechanism not being isothermal or isentropic. This will impact the density and compressibility calculations.

(4.0) ACCURACY REQUIREMENTS

Measurement of gas is following the trend of all flow measurement in that there is a continual push for greater perceived accuracy. However many of the gas installations are still orifice plates for which there is very little opportunity to improve on the basic orifice plate uncertainty, other than by calibration of each orifice individually. The drive has therefore concentrated on peripheral measurements such as temperature, pressure and density. The problem here is that these errors are now considerably smaller than the uncertainty of orifice plate measurement and so the improvements in uncertainty are becoming less realistic. On line densitometers can meter within ± 0.2 to $\pm 0.3\%$ subject to installation conditions, giving an orifice plate a $\pm 0.15\%$ mass flow error due to density. Thus for calculation of density in general it is required that this be better than 0.3% . Now pressure measurement error is $\pm 0.1\%$ FSD and assuming temperature errors to be $\pm 0.05\%$ FSD then using RMS errors the uncertainty of measurement of all other errors for p-T calculation must be better than $\pm 0.26\%$ to be better than densitometry. The largest error will come from the calculation of compressibility.

(5.0) DENSITY CALCULATION

The density for a real gas is given by:-

$$\rho = P \times M_w / ZRT$$

The compressibility factor is used to convert the equation from an ideal gas equation to a real gas. For an ideal gas $Z = 1$ and for a real gas it varies dependant upon temperature, pressure, gas and mixture. There are a number of methods of calculating the compressibility either using equations of state (Redlich - Kwong) or interpolations of data (NXL9). Each has a specific application and an area over which it is effective. Obviously there is a large amount of research currently going forward with the objective of achieving a universal law.

(6.0) COMPRESSIBILITY CORRECTIONS

(6.1) COMPRESSIBILITY - FACTOR DIAGRAMS

One of the earliest methods for compressibility was to use equations of state determined from generalised compressibility diagrams. The two main methods are the Nelson-Obert diagram and the Edmister-Pitzer diagram. Nelson-Obert diagrams are based on two parameter reduced temperature and pressure diagrams FIG3, based on 26 single component gases. Reduced pressure $P_r = P/P_c$ and reduced temperature T_r is defined as T/T_c , suffix : C being at the critical conditions e.i. the point of equal specific volume. For these gases the smoothed curves fit to within 1%. Once other gases are used the error increase to 2% for compressibility factors of 0.6 and above and up to 6% for factors between 0.3 and 0.6. Edmister-pitzer diagrams improve the prediction by introducing a third parameter factor ω called the acentric factor, based on how spherical the nature of the molecular force field of the gas. For simple fluids such as argon $\omega = 0$. They assumed that fluids with the same pVT relationship have the same ω , and the deviation is linear to adjust ω for the nature of the fluid then $Z = Z_0 + \omega Z_1$ where Z_0 is the simple compressibility and Z_1 , the deviation. The data can be derived from two diagrams FIG 4 and from the equation

$$\omega = (3 \log(P_r/14.7) / 7 (T_c/T_b - 1)) - 1$$

It is possible to obtain accuracies of better than $\pm 1\%$ over Z ranges of 0.6 - 1.0 for non-polar gases. A version of this method called the corresponding states equations is used by British gas. Combined with accurate data this method gives a low uncertainty for natural gas.

(6.2) CALCULATION METHODS

(6.21) REDLICH-KWONG EQUATIONS

The Redlich-Kwong equation is a two constant equation of state that may be adapted to calculate compressibility from T_r and P_r . Compressibility is given by

$$Z = 1 + A \frac{-AB}{A+Z} + \frac{A^2 B}{A^2 + Z^2}$$

where

$$A = \frac{0.0867 P_r}{T_r} \quad B = \frac{4.934}{T_r^{1.5}}$$

As the equation is non-linear it has to be solved iteratively, Newtons method being the simplest. FIG4 shows the deviation of Z with varying T_r and P_r for methane. At low pressures agreement with actual is good, better than 0.5%, but with increasing pressure and temperature the error increases significantly. Substantial modifications have been made to the basic theory by both Gaz de France and Ruhr gas but in general the equations are still not good at predictions at pressures above 60 bar absolute.

(6.22) BENEDICT-WEBB-RUBIN

The BWR equation is an 8 parameter equation of state. Compressibility can be derived from the two equations:

$$P = RTe + (B_0RT - A_0 - C_0/T^2)e^2 + (bRT - a)e^3 \dots$$

$$+ Ce^3(1 + \gamma e^2) \sqrt{T^2} - \gamma e$$

$$e = \frac{PM_w}{ZRT}$$

$A_0, B_0, C_0, a, b, C, \gamma, \alpha$ are empirical constants specific to the fluid concerned. This equation appears to have a good range of application although above 62 bar the deviation again appears to increase, errors of over 0.5% being likely.

(6.23) OTHER EQUATIONS OF STATE

There are a number of less commonly used equations of state such as the Peng-Robinson equation which is similar to the R-K equations. Emphasis seems to be on improving and 'honing' down the already proved equations to obtain improved uncertainty, by adding empirical corrections.

(6.3) INTERPOLATION METHODS (EMPIRICAL)

There are a number of empirical methods for determination of gas compressibility. They are based on the collection of experimental data, and then the production of curve fits to meet the data.

(6.31) AGA3 NX19)

The American gas association, rather than use equations of state undertook an extensive program of experiments to produce universal data. Several hundred experimental points were taken and a curve fit derived to give super-compressibility $F_{pv} = \sqrt{1/Z}$ where Z is compressibility. The square root function comes from the initial requirement being for orifice plates. The immediate problem with the equations is that for all values of temperature a pressure of 1.01325 bar a. leads to unity, i.e. $Z = 1$. This is not acceptable as it should only lead to 1 for an ideal gas. The basic curve fit for the equations are:-

$$F_{pv} = \frac{\sqrt{B/D - D + n/3\pi}}{1 + (0.00132/\tau^{3.25})}$$

Where

$$B = \frac{3 - mn^2}{9m\pi^2} \quad m = f(\tau)$$
$$D = (b + (b^2 + B^3)^{\frac{1}{2}})^{\frac{1}{3}} \quad n = f(\tau/m)$$
$$b = \frac{9n - 2mn^3}{54m\pi^3} - \frac{E}{2m\pi^2} \quad \pi = f(P)$$
$$\tau = f(T)$$

E = NX19 Table Extrapolation.

The tables were derived for a lean natural gas of specific gravity 0.6 containing no dilutants. T and P corrections were applied for gases with other gravities, and for gases with nitrogen and carbon dioxide additives. The following conditions over which NX19 is recommended are temperatures 230 to 390°K, pressure 340 bar and up to 15% nitrogen and carbon dioxide. This allows for compressibility determination for SG in the range 0.554 to 1.000.

To correct for the basic deficiencies of the concept, there are at least 6 different proposed corrections.

- 1) Texas Eastern Transmission Corp/British Gas proposed a modification given by $Z_{PT} = Z_{AGA} \times Z_T$ where PT represents corrected value, AGA is NX19 value and T is temperature correction at $P = 1.01325 \text{ bar a.}$
- 2) C.E.R.G. proposed a version:- $Z_{PT} = Z_{AGA} \times Z_S^2 / Z_n$ where S refers to $P = 1.01325 \text{ bar a.}$ and 15.55°C and n refers to $P = 1.01325 \text{ bar a.}$ and 0°C.
- 3) Herning and Wolowski (Ruhr Gas) proposed two versions, one based on translocation of the scale, implying that Z_{AGA} is unity for $P = 0$ rather than 1.01325 bar a.
- 4) They also proposed that $Z_{PT} = Z_{AGA} \times Z_n$
- 5) Gaz de France proposed that $Z_{PT} = Z_{AGA} \times Z_S$
- 6) A further concept idea by Gas de France the change would be

$$Z_{PT} = Z_{AGA} - (1 - Z_T) \text{ This is not based on scientific evidence but seems to give reasonable correction up to } 80 \text{ bar a.}$$

Corrections 2, 3 and 4 give answers at $P = 1.01325 \text{ bar a.}$ which is not correct.

These corrections all show a reduction in error but they do not correct the inherent defects in the basic empirical relation determined from experimental error.

The NX19 equation is very specific to natural gas and cannot be used for other gases. In general the NX19 equations do not seem to perform as well as some other methods except at very high pressure, above 82 bar and high SG, although within specific ranges of pressure, temperature methane content the performance can be very impressive, RMS errors of the order of 0.1%

(6.32) AGA 8 GRI

The latest method of compressibility calculation is the GRI equations now incorporated in AGA 8. It is a semi-empirical method based initially on an equation of state, with fine tuning from empirical data. The basic equation is given by $Z = Z_0(T_r, \rho_r) + \delta Z_\delta(T_r, \delta_r)$

where δ is a parameter similar to the acentric factor.

ρ = molar density, E = energy parameter and σ separation, parameter obtained from :-

$$T_r = KT/\epsilon \quad , \quad e_r = e\sigma^3$$

$$\sigma^3 = 0.3189/\epsilon_c \quad , \quad \epsilon/k = T_c/1.2593, \quad t = (T_r)^{-0.5}$$

Z_0 was determined from selected experimental data, second virial coefficient, enthalpy departure and vapour pressure data for methane, giving

$$Z_0 = 1 + (a_1 + a_2t + a_3t^2 + a_4t^3 + a_5t^4 + a_{27}t^5 + a_{17}t^7 + a_{16}t^8)e_r \\ + (a_6t + a_7t^4 + a_8t^5 + a_{18}t^{10})e_r^2 + (a_9t + a_{10}t^2 + a_{11}t^3)e_r^3 \\ + (a_{12}t^2 + a_{13}t^6)e_r^5 + a_{14}t^6e_r^2 + (1 + a_{15}e_r^2)\exp(-a_{15}e_r^2)$$

Z_8 is found similarly with data from ethane, propane, nitrogen, carbon dioxide etc. up to 11 constituents and is given by:-

$$Z_8 = (a_{19}t + a_{20}t^4)e_r + (a_{23} + a_{24}t^4)e_r^2 + (a_{25}t^4 + a_{26}t^5)e_r^3 \\ + a_{21}t^2e_r^5 + a_{22}t^6e_r^2(1 + a_{15}e_r^2)\exp(-a_{15}e_r^2)$$

a_i in the equation are equation of state constants.

While this equation set is still relatively new it does appear to be giving high quality answers. For general natural gas the compressibility may be calculable to within a 0.3% absolute deviation up to 150bar a. Perhaps however its greatest feature is that it does have more general application than the other methods, from pure gases through to complex mixtures.

(6.33) IUPAC TABLES

The international union for Pure and Applied Chemistry (IUPAC)

have produced tables for a variety of gases. In particular they

have produced useful extrapolation of tables for Ethylene and high

and low pressures. For low pressure this takes the form $Z = \sum_{i=0}^2 \sum_{j=0}^4 B_{ij} T^{-j} e^i$

Where the coefficients are obtained from IUPAC tables.

(7.0) SUMMARY

The paper is a very loose summary of the methods for calculating density, on line. It misses out several methods of compressibility calculation such as Standing-Katz and Vennix-Kobayashi. Overall the picture that emerges is that all of the methods have use in different applications, and maybe a manufacturer of flow computers has to include them all in

software with a preference selection based on pressure, temperature content, density range combined with mind reading software for personal preference. Perhaps the latest method the GRI will allow a rationalisation if in the end it is shown to have the range it appears to have.

From a practical stand point it would seem more suitable to combine two or preferably three methods, calculation, direct density by densitometer and density by gas chromatography to obtain a reliable answer for density. A summary of the limitations of the different methods are below based on the references given.

METHOD OF COMPRESSIBILITY DETERMINATION	SENSIBLE PRESSURE RANGE BAR	PROCESS FLUID	MINIMUM ERROR	OVERALL ERROR *
NELSON - OBERT		Polar Gases	+ - 1%	+ - 4 - 6%
EDMISTER - PITZER		Polar & Non-Polar Gases	+ - 1%	+ - 3%
REDLICH-KWONG **	50 bar A.	Various	+ -0.5%	+ - 2% 50-100bar A
BENEDICT-WEBB-RUBIN	80 bar A	Various	+ -0.4%	+ - 1% *** with offset
AGA3 NX19	100bar A	Natural Gas & Dilutents	+ -0.5%	+ - 1% 100-150Bar A
AGA 8 GRI	150bar	All Gases	+ -0.15% for natural Gas	
IUPAC - low pressure		Ethylene	+ -0.2%	
STANDING-KATZ	150bar	Natural Gases	+ -0.6%	

* A combination of offset and linearity errors have been combined

** Depends on modifications

*** Reference 8 gives much better results ⁺-0.2 up to 150 Bar A for Natural gas.

The results from all the references are subject to wide interpretation and so the table is necessarily broad in its error band. Also these errors are purely those obtained under 'ideal' experimental conditions and are likely to be larger under process conditions

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LIST OF SYMBOLS

\dot{M}	=	Mass Flow
K	=	Flow Constant
ΔP	=	Orifice Differential
ρ	=	Density
f	=	Turbine/Vortex Frequency
P	=	Pressure of Fluid
P_c	=	Critical Pressure
M_w	=	Mole Weight
R	=	Universal Gas Constant
Z	=	Compressibility factor
T	=	Absolute Temperature
T_c	=	Critical Temperature
T_B	=	Boiling Temperature
ω	=	Accentric Factor

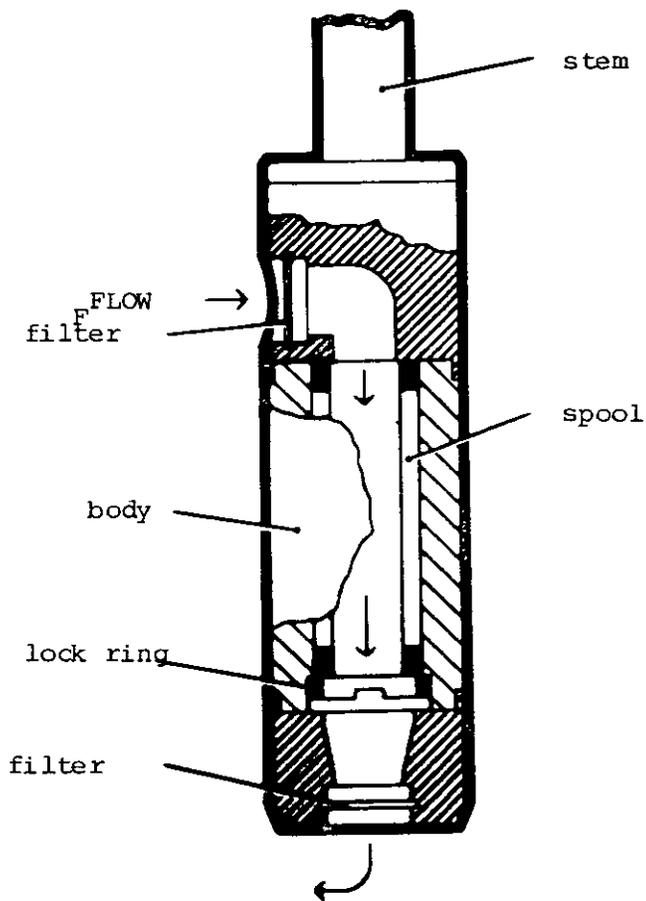


FIG. DENSITOMETER

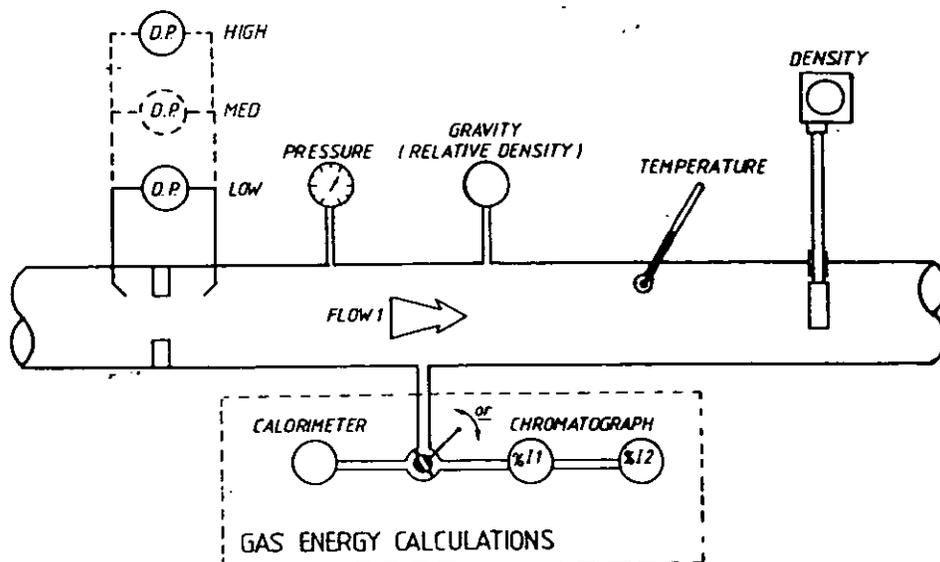


FIG.2 GAS ORIFICE INSTALLATION

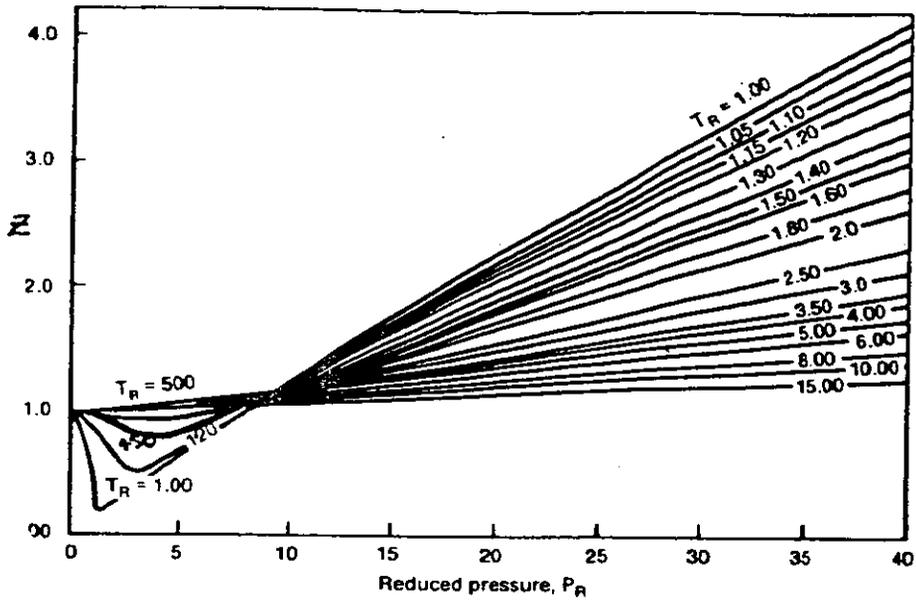


FIG. 3 NELSON-OBERT COMPRESSIBILITY DIAGRAM

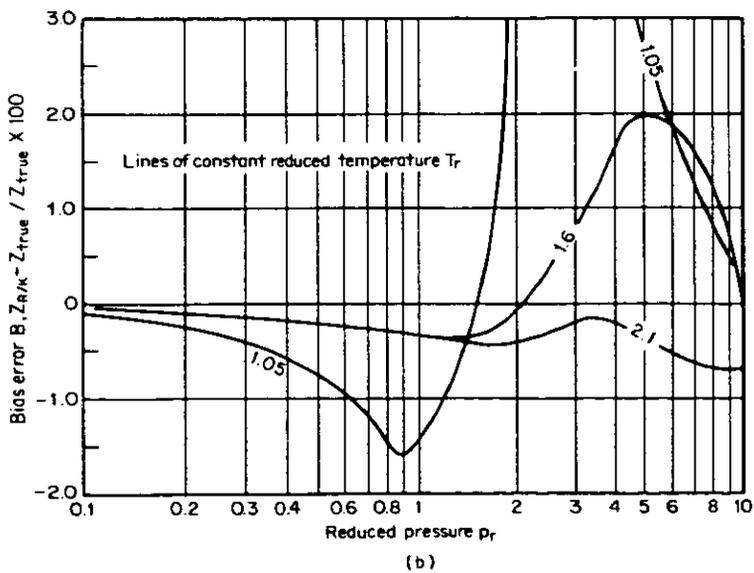


FIG. 4 ERROR CURVES FOR METHANE FOR THE BASIC REDLICH-KWONG EQUATION

D I S T R I G A Z
BRUSSELS
BELGIUM

OCTOBER 1987

THE D&H Z-METER USED AS VOLUME CORRECTING DEVICE
IN TURBINE METERING STATIONS.

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METERING DEPARTMENT

Summary

This paper describes a method to determine globally the correction factor, using a D&H Z-meter, for the normalization of the gross volume flow rate measured by a turbine meter in a natural gas metering station.

1 INTRODUCTION

1.1 History

Since 1973, confronted with very large gas flow measurements, Distrigaz decided to develop orifice plate metering stations equipped with high precision digital instruments interfaced with a central minicomputer. The pressure and differential pressure were measured by Desgranges & Huot automatic deadweight balances (maximum error on reading values is lower than .1%). The base density and the compressibility of the gas were constant factors.

In the year 1975, the arrival of North Sea gas, of variable composition, caused additional measurements. The objective was to measure if possible all the parameters of the ISO 5167 equation with a maximum allowable error of .1% of the measured value, together with a long term stability of several years without recalibration. At that moment the existing density meters and reference density meters had accuracies of about .2% and were dependent on the real gas composition. Moreover, there was no method accurate enough to predict the compressibility factor of natural gases from gas composition. The A.G.A. NX-19 method, depending on the gas composition, can reach a 1% error at high pressure for gases containing large amounts of higher hydrocarbons.

All these requirements and facts led Distrigaz to request the french manufacturer Desgranges & Huot to develop and build original devices independant of the gas composition: a buoyancy based density meter using a 1 liter sphere and a device measuring the compressibility factor, in fact the factor $(p \cdot Z_n) / Z$, the "Z-meter". The density at reference conditions ($p_n = 1.01325$ bar, $T_n = 273.15$ K) is calculated from the equation : $\rho_n = \rho \cdot (p_n \cdot T \cdot Z) / (p \cdot T_n \cdot Z_n)$.

Later it appeared that the Z-meter integrated in volumetric metering

systems was the ideal corrector for variable composition gases.

At the present time, more than 25 Z-meters are in operation (six from 1976 and six from 1979 in orifice metering stations, the others later in turbine meter metering stations) and show performances exceeding the most optimistic expectations. Every check of the Z measurement on the site with pure methane and/or pure nitrogen shows a better than .1% agreement with the pure component data from the table. Due to its qualities and the ease with which it can be put into service, this instrument is also used intensively in laboratories. As several papers have already been written on it with regard to this application, it seemed useful to recall its industrial origin.

Recently, the Van der Waals Laboratory in Amsterdam sponsored by the "Groupe Européen de Recherches Gazières" (GERG) and the University of Oklahoma sponsored by the "Gas Research Institute" (GRI) have independently developed highly accurate equations to predict the compressibility factors for natural gases from knowledge of temperature, pressure and gas composition typically with an accuracy of 0.1 % for custody transfer conditions. But the uncertainties attached to the gas analyses and to the line pressure measurements have to be added to those of the equations. Another thing is that the programs using these equations take a big part of the computer memory and cannot run in our minicomputers in their actual state .

1.2 Base equation in volumetric metering systems

Turbine meters measure a gross volume flow ,i.e. the gas flow at pressure and temperature conditions of the meter. As it is customary to express gas quantities ,not in terms of mass, but in terms of volume, it is necessary to standardize the base conditions of this volume flow.

The "base" conditions referred to in this paper are the "normal" conditions, i.e. pressure $p_n = 1.01325$ bar and temperature $T_n = 273.15K$. The symbol for "normal m3" is m3(n). These conditions are

commonly used in continental western Europe.

The relation between the normalized volume Q_c and the gross volume Q is defined by the following expression:

$$Q_c \text{ (m}^3 \text{ (n))} = Q \text{ (m}^3) \frac{p \ T_n \ Z_n}{p_n \ T \ Z} \quad (1)$$

where:

p is the thermodynamic pressure of the gas expressed in bar.

p_n is the base pressure (1.01325 bar)

T is the thermodynamic temperature of the gas.

T_n is the base temperature of the gas. (273.15 K)

Z is the compressibility factor of the gas at pressure p et temperature T .

Z_n is the compressibility factor at base conditions.

The factor $\frac{p \ Z_n \ T_n}{p_n \ Z \ T}$ is called "normalization (or "correction") factor"

The "Z-meter" is able to measure globally the factor:

$$\frac{p \ Z_n \ T_n}{p_n \ Z} \quad (\text{at the temperature of the Z-meter } T_n)$$

of gases, within a certain pressure and temperature range, with an accuracy better than .1 %. The additional measurement of the line temperature T_1 is therefore sufficient to calculate the normalization factor.

2 COMPRESSIBILITY FACTOR

Conventional signs :

The symbol "T" means that the temperature is expressed in K, and "t" means that it is expressed in °C.

2.1 Definition

The equation of state of an ideal gas is written :

$$pV = nRT$$

where :

n is the number of moles contained in volume V,

R is the universal gas constant,

p is the thermodynamic pressure of the gas,

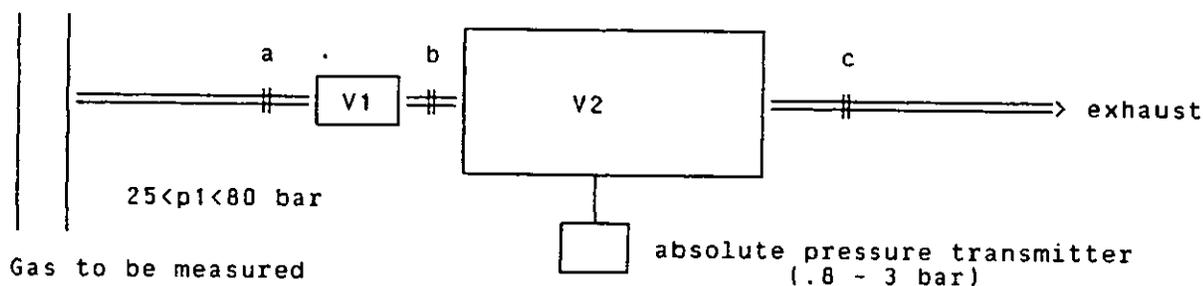
T is the thermodynamic temperature of the gas.

Real gases do not behave exactly as described by this law. To take this into account, the equation of state for real gases becomes :

$$pV = nZRT$$

Factor Z, which is a function of pressure and temperature, is called the "compressibility factor". Its value is therefore representative of the non-ideality of the gas. All gases being ideal at zero pressure, Z tends towards one when the pressure tends towards zero. This fact is essential to understand the various methods described below.

2.2 Operating principle of the Z-meter



The Z-meter is composed of two volumes V_1 and V_2 of different sizes surrounded by a massive metallic wall of great thermal inertia. The small volume V_1 (its capacity is about 20 cc) ,consisting of a 6 mm OD tube, is welded as a spiral around the large cylindrical volume V_2 to improve thermal exchanges between them . The two volumes are isolated by three valves:

- the inlet valve a which links volume V_1 to the gas line of which compressibility factor has to be measured
- the by-pass valve b which separates the two volumes
- the exhaust valve c which links volume V_2 to the atmosphere

The three interdependent valves are driven by one pneumatic motor controlled by a solenoid valve.

The operation of the Z-meter is cyclic and may be divided into two phases :

- state 1 : valves a and c are open and valve b is closed.

The law of real gases applies for the two volumes :

$$p_1 V_1 = n_1 Z_1 RT_1 \quad (1)$$

$$p_2 V_2 = n_2 Z_2 RT_2 \quad (2)$$

- where :
- n_1, n_2 are the numbers of moles of the gas contained respectively in volumes V_1 and V_2
 - p_1 is the pressure of the gas to be measured
 - p_2 is the atmospheric pressure
 - T is the temperature of the metal mass of the apparatus

- state 2 : valves a and c are closed and valve b is opened. The gas initially contained in volume V_1 expands to fill the total volume $V_1 + V_2$.

Once thermal equilibrium is attained, the pressure of the gas is stabilized at pressure p_3 .

Temperature T is the same as before expansion, due to the large thermal buffer and the small amount of expanded gas. In this situation, the thermodynamic state is :

$$p_3 (V_1 + V_2) = (n_1 + n_2) Z_3 RT \quad (3)$$

Combining these three equations and introducing the ratio $A = V_2 / V_1$:

$$\frac{p_1}{Z_1} = \frac{p_3 (A+1)}{Z_3} - \frac{p_2 A}{Z_2} \quad (4)$$

For gas metering, it is not the factor Z, i.e. the compressibility factor in p and t line conditions, which is important but the ratio between this factor and the factor Z_n , i.e. the compressibility factor in normal conditions:

Conventionally: $K = Z(p,t)/Z_n$

In the subsequent text, the "compressibility factor" or "factor Z" means the ratio K.

Multiplying the equation (4) by Z_n , it becomes:

$$\frac{p_1}{K_1} = \frac{p_3 (A+1)}{K_3} - \frac{p_2 A}{K_2} \quad (5)$$

2.3 Calculation methods

In equation (5), A is known by the calibration of the Z-meter (see section 2.4), P_2 and P_3 are measured by the same pressure transmitter. It then remains to determine K_2 and K_3 .

The method is based on an iterative calculation of K_2 and K_3 .

To apply this method, the line pressure P_1 must be measured with an accuracy of approximately one percent, which is easily obtained by good industrial transmitters.

On an isotherm, in the metering pressure range of 0-80 bar, the $K(p,t)$ function may be expressed by :

$$K(p,t) = 1 + A t + B (p-1.01325) + C (p-1.01325)^2 \quad (6)$$

where : A = 2.8E-5
 C = 2.0E-6

The coefficients A and C are average coefficients calculated for natural gases and vary little from one gas to another. The coefficient A takes into account the temperature dependance of K at 1.01325 bar. The variability with gas composition of coefficient C is larger than that of coefficient A.

It is possible to improve the method through specific determination of coefficient C for a gas or a family of gases, possibly as a function of temperature. For example, for the mixture 50% CH₄ / 50% N₂ , the C factor is 3.2E-5 which causes a difference lower than 2.E-4 for the K factor at 50 bar . This correction is important especially for laboratory measurements where the degree of accuracy must be as high as possible. In that case, the determination of the compressibility factor of an unknown gas is done in two steps. The first step consists to determine the K factors at several pressures with C=0 and then to calculate the C factor of equation (6) by a "least squares method" fit. The second step consists to reenter the calculation processus using the real C value . The non-linearity error is then eliminated .

If C is fixed, the only unknown quantity in equation (6) is coefficient "B" which represents the "slope" of the function.

The first step of the calculation is to fix the initial values :
 $K_2 = 1$ and $K_3 = .998$ for example.

Through equation (5) and as p_1 is measured by a transmitter, K_1 can be calculated . It is then possible, through equation (6), to calculate a first approximation of B as follows:

$$B = \frac{(K_1 - (1 + A t) - C (p_1 - 1.01325)^2)}{(p_1 - 1.01325)}$$

Equation (6) is then totally defined and allows the calculation of two new values K_2' and K_3' . These two values make it possible to calculate K_1' using equation (5) and so on until the difference between two successive K_1 values is lower than 1.E-4 .

In practice, three steps are sufficient.

2.4 Calibration of the Z-meter

In equation (5) of section 2.2 ,the factor A is known and the values of p_2 and p_3 are measured by the same absolute pressure transmitter.

In theory, it is very tempting to try to measure volume ratio A directly, which would make the Z-meter a fundamental apparatus. However, this is impossible with the desired degree of accuracy.

The calibration of the Z-meter consists to determine the ratio A, using pure gases from which the compressibility table is precisely known, and to calculate the transfer function of its associated pressure transmitter. Nitrogen and methane are the most frequently used gases. Helium and argon were also used in evaluating the performances of the Z-meter prototypes.

2.4.1 Absolute Pressure Transmitter

Before determining the A factor, the absolute pressure transmitter must be calibrated. This is a "Rosemount" transmitter with an analog output of 4-20 mA. The current is converted into voltage by a 50 Ohms Sfernice shunt (accuracy $5.E-5$) .

The voltage measurements are provided by Hewlett-Packard 3456A multimeters of which accuracy over the 1 V range is better than .0025%. A Fluke 3320 voltage standard is used for periodical checking the multimeters. The pressure standard is a Desgranges & Huot type 8000 deadweight tester (0 to 10 bar abs). Its accuracy is .01 % of the measurement.

The transmitter, of which nominal span was 0 to 7 bar abs., is adapted to .8 to 3 bar abs. In fact, p_2 ,the atmospheric pressure, is always higher than .8 bar, and p_3 ,the pressure after expansion, is always lower than 3 bar at a maximum line pressure of 80 bar and with

the A ratio that has been chosen. After setting, numerous measurements are taken at multiple points of span. The read voltages and the corresponding absolute pressure values are noted.

The voltage second-degree polynomial expressed in "points" (volts multiplied by 1.E+5), is calculated as close as possible, in the "least squares" sense, to the pressure/voltage couples:

$$p = a + b V + c V^2$$

A critical examination of polynomial quality approximation may lead to reject the transmitter if it behaves excessively in "S". In such a case, the second degree form is not appropriate .

```

*****
* Transmitter:8613744
*
* Voltage      Stand.pressure  Calc. pressure  Absolute
* Points       bar abs.         bar abs.        Deviation
*
* 100140       3.0020           3.0022         -.213E-03
* 92845        2.8019           2.8018         .652E-04
* 85590        2.6017           2.6025         -.774E-03
* 78281        2.4016           2.4016         -.244E-04
* 71011        2.2015           2.2018         -.306E-03
* 63714        2.0013           2.0010         .283E-03
* 56473        1.8012           1.8018         -.618E-03
* 49176        1.6011           1.6010         .857E-04
* 41905        1.4009           1.4008         .157E-03
* 34644        1.2008           1.2008         .466E-04
* 27419        1.0007           1.0017         -.987E-03
* 20136        .8005            .8009          -.339E-03
* 20120        .8005            .8004          .107E-03
* 27376        1.0007           1.0005         .198E-03
* 34623        1.2008           1.2002         .636E-03
* 41885        1.4009           1.4002         .727E-03
* 49175        1.6011           1.6009         .124E-03
* 56450        1.8012           1.8012         .150E-04
* 63708        2.0013           2.0009         .448E-03
* 71000        2.2015           2.2015         -.393E-05
* 78295        2.4016           2.4020         -.396E-03
* 85563        2.6017           2.6017         -.185E-04
* 92858        2.8019           2.8022         -.292E-03
* 100100       3.0020           3.0009         .108E-02
*
* a= .24539624E+00
* b= .27602088E-04
* c=-.73284406E-12
*****

```

2.4.2 A Ratio

Now the evaluation of the A ratio may begin . It is a question of

making the Z-meter work at different pressures between 30 and 70 bar using a gas of high purity as standard gas, for example nitrogen or methane . The pressure of the gas is measured by a Desgranges & Huot type 5500 deadweight standard balance (.005 % accuracy) . The atmospheric pressure measured by two barometers (.01% accuracy) in the laboratory has to be added to this pressure to obtain the absolute pressure p_1 .

Pressures p_2 and p_3 are measured by the absolute pressure transmitter using the previously calculated calibration polynomial.

The temperature of the Z-meter is measured, with an accuracy better than .05°C, by a double platinum resistance of which the value at 0°C was previously determined on a .0001% accuracy measuring bridge. The standard is a "Leeds and Northrup" platinum reference thermometer supplied with coefficients corresponding to the "IPTS-68" formulae, traceable to NBS standard .

The pure gas compressibility factors being known, all the parameters of equation (5) are defined and the A ratio can be calculated.

These measurements being repeated at different pressures, a series of A values are collected and averaged . At this step, standard deviation is generally better than .01 %.

Z-meter D&H :265
 Calibration gas :CH4
 Transmitter :8613744
 P=a+b*V+c*V*V : a= .2453971E+00
 : b= .2759763E-04
 : c=-.7323275E-12
 Z-meter temperature 1 :RO=100.057 Ohms
 Z-meter temperature 2 :RO= 99.927 Ohms

```
*****
* P1 P2 P3 T Z1 Z2 Z3 A *
*****
* 71.0483 1.01783 2.57599 19.86 .87834 .99813 .99526 49.9204 *
* 71.0483 1.01775 2.57595 19.87 .87834 .99813 .99526 49.9191 *
* 71.0481 1.01769 2.57591 19.87 .87835 .99813 .99526 49.9179 *
* 71.0479 1.01753 2.57574 19.87 .87836 .99813 .99526 49.9177 *
* 71.0479 1.01745 2.57563 19.88 .87837 .99813 .99526 49.9183 *
* 71.0479 1.01746 2.57561 19.88 .87837 .99813 .99526 49.9188 *
* 71.0479 1.01743 2.57559 19.89 .87838 .99813 .99526 49.9181 *
* 71.0479 1.01751 2.57566 19.89 .87839 .99813 .99526 49.9179 *
* 71.0479 1.01755 2.57570 19.90 .87840 .99813 .99526 49.9174 *
* 71.0479 1.01757 2.57565 19.90 .87841 .99813 .99526 49.9190 *
*****
```

* Mean A :49.9185 *

```
*****
* 61.0436 1.01791 2.33113 19.91 .89374 .99813 .99571 49.9185 *
* 61.0435 1.01776 2.33097 19.92 .89376 .99813 .99571 49.9182 *
* 61.0435 1.01771 2.33095 19.93 .89377 .99813 .99571 49.9165 *
* 61.0435 1.01769 2.33096 19.94 .89378 .99813 .99571 49.9151 *
* 61.0434 1.01765 2.33087 19.94 .89379 .99813 .99571 49.9163 *
* 61.0434 1.01765 2.33084 19.95 .89380 .99813 .99572 49.9168 *
* 61.0433 1.01764 2.33083 19.95 .89380 .99813 .99572 49.9166 *
* 61.0433 1.01757 2.33074 19.96 .89381 .99813 .99572 49.9170 *
* 61.0432 1.01758 2.33070 19.96 .89382 .99813 .99572 49.9184 *
* 61.0432 1.01751 2.33069 19.96 .89382 .99813 .99572 49.9160 *
*****
```

* Mean A :49.9169 *

```
*****
* 51.0386 1.01774 2.09311 19.97 .90994 .99813 .99615 49.9179 *
* 51.0386 1.01744 2.09288 19.97 .90995 .99813 .99615 49.9148 *
* 51.0385 1.01745 2.09285 19.98 .90995 .99813 .99615 49.9167 *
* 51.0385 1.01746 2.09281 19.98 .90996 .99813 .99615 49.9183 *
* 51.0385 1.01733 2.09278 19.98 .90996 .99813 .99615 49.9139 *
* 51.0384 1.01730 2.09271 19.98 .90996 .99813 .99615 49.9152 *
* 51.0383 1.01726 2.09267 19.99 .90997 .99813 .99615 49.9150 *
* 51.0383 1.01722 2.09261 19.99 .90997 .99813 .99615 49.9160 *
* 51.0383 1.01723 2.09262 19.99 .90997 .99813 .99615 49.9157 *
* 51.0384 1.01735 2.09274 19.99 .90997 .99813 .99615 49.9159 *
*****
```

* Mean A :49.9159 *

```
*****
* 41.0338 1.01733 1.86245 19.99 .92675 .99813 .99658 49.9151 *
* 41.0337 1.01714 1.86229 20.00 .92675 .99813 .99658 49.9128 *
* 41.0337 1.01705 1.86219 20.00 .92675 .99813 .99658 49.9136 *
* 41.0336 1.01700 1.86213 20.00 .92676 .99813 .99658 49.9145 *
* 41.0337 1.01694 1.86210 20.00 .92676 .99813 .99658 49.9124 *
* 41.0336 1.01692 1.86208 20.00 .92676 .99813 .99658 49.9125 *
* 41.0335 1.01690 1.86208 20.00 .92676 .99813 .99658 49.9113 *
* 41.0336 1.01690 1.86207 20.01 .92676 .99813 .99658 49.9120 *
* 41.0336 1.01700 1.86210 20.01 .92676 .99813 .99658 49.9156 *
* 41.0336 1.01695 1.86210 20.01 .92676 .99813 .99658 49.9128 *
*****
```

* Mean A :49.9133 *

```
*****
* 31.0291 1.01687 1.63938 20.01 .94407 .99813 .99699 49.9123 *
* 31.0291 1.01678 1.63931 20.01 .94407 .99813 .99699 49.9106 *
* 31.0291 1.01677 1.63928 20.01 .94407 .99813 .99699 49.9123 *
* 31.0291 1.01677 1.63929 20.02 .94407 .99813 .99699 49.9113 *
* 31.0291 1.01682 1.63935 20.02 .94408 .99813 .99699 49.9105 *
* 31.0291 1.01682 1.63935 20.02 .94408 .99813 .99699 49.9097 *
* 31.0291 1.01680 1.63932 20.02 .94408 .99813 .99699 49.9115 *
* 31.0291 1.01673 1.63926 20.02 .94408 .99813 .99699 49.9099 *
* 31.0291 1.01682 1.63937 20.02 .94408 .99813 .99699 49.9081 *
* 31.0291 1.01683 1.63936 20.02 .94408 .99813 .99699 49.9104 *
*****
```

* Mean A :49.9107 *

Mean A :49.9151 Standard deviation =.00304/49.9151=.006%

It would be possible to stop at this point and consider the Z-meter calibrated. However, another calculation is done to eliminate the small remaining pressure effects .

2.4.3 New pressure transmitter coefficients

In fact, if we look at the results, we can see a small variation of ratio A with the pressure. This effect can be eliminated by recalculating new coefficients for the absolute transmitter using the mean A value previously determined .

A lot of compressibility values are collected, with the pure gas, all over the working pressure range. Each voltage value from the pressure transmitter in situations p_2 and p_3 , is memorized.

Pressure p_3 , expressed in bar, is calculated with the equation (5) in section 2.2 using the mean A value determined at the preceding calibration step. Pressure p_1 is always determined by the standard balance associated with high precision barometers.

The new coefficients of the second-degree polynomial fitting the pairs (voltage - pressure p_3) are calculated. This polynomial now constitutes the global "transmitter - Z-meter" conversion function.

For example, for the transmitter N° 8613744 ,the new coefficients are :

a= .24559733E+00
b= .27587092E-04
c=-.61207614E-12

2.4.4 Final A value

The last step consists to recalculate, at each pressure range, the A values using equation (5) and the new coefficients of the absolute pressure transmitter and to take the average of this values as final ratio A. The standard deviation is then always better than .005% .

Z-meter D&H :265
 Calibration gas :CH4
 Transmitter :8613744
 P=a+b*V+c*V*V : a= .2455973E+00
 : b= .2758709E-04
 : c=-.6120761E-12
 Z-meter temperature 1 :RO=100.057 Ohms
 Z-meter temperature 2 :RO= 99.927 Ohms

```

*****
* P1 P2 P3 T Z1 Z2 Z3 A *
*****
* 71.0483 1.01783 2.57616 19.86 .87834 .99813 .99526 49.9148 *
* 71.0483 1.01775 2.57612 19.87 .87834 .99813 .99526 49.9135 *
* 71.0481 1.01769 2.57608 19.87 .87835 .99813 .99526 49.9123 *
* 71.0479 1.01753 2.57591 19.87 .87836 .99813 .99526 49.9121 *
* 71.0479 1.01745 2.57580 19.88 .87837 .99813 .99526 49.9127 *
* 71.0479 1.01746 2.57578 19.88 .87837 .99813 .99526 49.9133 *
* 71.0479 1.01743 2.57576 19.89 .87838 .99813 .99526 49.9126 *
* 71.0479 1.01751 2.57583 19.89 .87839 .99813 .99526 49.9123 *
* 71.0479 1.01755 2.57587 19.90 .87840 .99813 .99526 49.9119 *
* 71.0479 1.01757 2.57582 19.90 .87841 .99813 .99526 49.9135 *
*****
* Mean A :49.9129 *
*****
* 61.0436 1.01791 2.33122 19.91 .89374 .99813 .99571 49.9150 *
* 61.0435 1.01775 2.33106 19.92 .89376 .99813 .99571 49.9146 *
* 61.0435 1.01771 2.33105 19.93 .89377 .99813 .99571 49.9129 *
* 61.0435 1.01769 2.33105 19.94 .89378 .99813 .99571 49.9115 *
* 61.0434 1.01765 2.33096 19.94 .89379 .99813 .99571 49.9127 *
* 61.0434 1.01765 2.33094 19.95 .89380 .99813 .99571 49.9132 *
* 61.0433 1.01764 2.33092 19.95 .89380 .99813 .99572 49.9129 *
* 61.0433 1.01757 2.33083 19.96 .89381 .99813 .99572 49.9135 *
* 61.0432 1.01758 2.33079 19.96 .89382 .99813 .99572 49.9149 *
* 61.0432 1.01751 2.33078 19.96 .89382 .99813 .99572 49.9124 *
*****
* Mean A :49.9134 *
*****
* 51.0386 1.01774 2.09315 19.97 .90994 .99813 .99615 49.9163 *
* 51.0386 1.01744 2.09292 19.97 .90995 .99813 .99615 49.9131 *
* 51.0385 1.01745 2.09288 19.98 .90995 .99813 .99615 49.9150 *
* 51.0385 1.01746 2.09285 19.98 .90996 .99813 .99615 49.9166 *
* 51.0385 1.01733 2.09281 19.98 .90996 .99813 .99615 49.9123 *
* 51.0384 1.01729 2.09274 19.98 .90996 .99813 .99615 49.9136 *
* 51.0383 1.01726 2.09271 19.99 .90997 .99813 .99615 49.9134 *
* 51.0383 1.01722 2.09265 19.99 .90997 .99813 .99615 49.9144 *
* 51.0383 1.01723 2.09266 19.99 .90997 .99813 .99615 49.9140 *
* 51.0384 1.01735 2.09277 19.99 .90997 .99813 .99615 49.9142 *
*****
* Mean A :49.9143 *
*****
* 41.0338 1.01733 1.86245 19.99 .92675 .99813 .99658 49.9153 *
* 41.0337 1.01713 1.86229 20.00 .92675 .99813 .99658 49.9130 *
* 41.0337 1.01705 1.86219 20.00 .92675 .99813 .99658 49.9138 *
* 41.0336 1.01700 1.86213 20.00 .92676 .99813 .99658 49.9147 *
* 41.0337 1.01694 1.86209 20.00 .92676 .99813 .99658 49.9127 *
* 41.0336 1.01692 1.86207 20.00 .92676 .99813 .99658 49.9127 *
* 41.0335 1.01690 1.86208 20.00 .92676 .99813 .99658 49.9115 *
* 41.0336 1.01690 1.86206 20.01 .92676 .99813 .99658 49.9122 *
* 41.0336 1.01700 1.86210 20.01 .92676 .99813 .99658 49.9158 *
* 41.0336 1.01695 1.86209 20.01 .92676 .99813 .99658 49.9130 *
*****
* Mean A :49.9135 *
*****
* 31.0291 1.01687 1.63935 20.01 .94407 .99813 .99699 49.9143 *
* 31.0291 1.01678 1.63929 20.01 .94407 .99813 .99699 49.9127 *
* 31.0291 1.01677 1.63926 20.01 .94407 .99813 .99699 49.9143 *
* 31.0291 1.01677 1.63927 20.02 .94407 .99813 .99699 49.9133 *
* 31.0291 1.01682 1.63932 20.02 .94408 .99813 .99699 49.9125 *
* 31.0291 1.01681 1.63933 20.02 .94408 .99813 .99699 49.9117 *
* 31.0291 1.01680 1.63929 20.02 .94408 .99813 .99699 49.9135 *
* 31.0291 1.01673 1.63924 20.02 .94408 .99813 .99699 49.9119 *
* 31.0291 1.01681 1.63935 20.02 .94408 .99813 .99699 49.9101 *
* 31.0291 1.01683 1.63933 20.02 .94408 .99813 .99699 49.9124 *
*****
* Mean A :49.9127 *
*****

```

Mean A :49.9133 Standard deviation =.00130/49.9133=.003%

Now, the Z-meter is calibrated and characterized by 4 coefficients :
A, a, b, c.

2.4.5 Last laboratory check

An ultimate verification is made before the Z-meter leaves the laboratory for a metering station to evaluate the accuracy of the Z-meter in its outside working conditions. The Z-meter is equipped with its field instruments which have been previously calibrated, i.e. the gage line pressure transmitter for p_1 measurements and the temperature transmitter for the Z-meter temperature measurements. Several Z-meter expansions are carried out at different pressure levels with another pure gas than the one used for the calibration. For example, if the Z-meter has been calibrated with methane, the verification is done with nitrogen. The measured Z values are compared with the compressibility factors calculated from the table. The results showed until now always a very good agreement between those values. The error is lower than .01% at 50 and 60 bar, and lower than .03% at 40 and 70 bar.

Comparison with Z table for N2

Z-meter O&H : 265
Calibration gas : CH4
A factor : 49.9133
Transmitter : 8613744
P=a+b*V+c*V*V : a= .2455973E+00
 : b= .2758709E-04
 : c= -.6120761E-12
Line pressure transmitter : 8613720
P=a+b*V+c*V*V : a= -.1856433E+02
 : b= .8795945E-03
 : c= -.1219839E-10
Z-meter temperature 1 : RO=100.057 Ohms
Z-meter temperature 2 : RO= 99.927 Ohms

```
*****
*      P      T      Z      ZTABLE  DEV.*1E-3*
*****
* 71.0806    21.43    .99640    .99614    .26  *
* 71.0810    21.44    .99639    .99615    .24  *
* 71.0813    21.45    .99637    .99615    .22  *
* 61.0595    21.47    .99517    .99518    -.01  *
* 61.0591    21.48    .99518    .99518    -.00  *
* 61.0588    21.49    .99516    .99519    -.03  *
* 51.0592    21.51    .99483    .99471    .12  *
* 51.0581    21.52    .99481    .99472    .09  *
* 51.0583    21.53    .99479    .99472    .06  *
* 41.0628    21.56    .99511    .99475    .36  *
* 41.0616    21.58    .99507    .99475    .32  *
* 41.0616    21.59    .99506    .99476    .31  *
*****
```

2.5 Method of transferring Z

This method, developed by Distrigaz, is useful for predicting the value $K'(p',t')$ from the value $K(p,t)$, i.e. in other pressure and temperature conditions, without need for the gas composition. Its existence is fundamental in the Distrigaz metering systems.

2.5.1 Transferring in temperature ($40 < p < 70$ bar):

$$K_f = (1 + (A + B K_i)(t_f - t_i)) K_i$$

where A = 1.8584E-2
 B = -1.8864E-2

The value of K_i must be between .80 and .94

The significance of this formula is that the local derivative of K in relation to the temperature, on an isobar, is a function of the local value of K. To get the most from this formula, it should be iterated in steps of 1 °C maximum. The smaller the step, the more symmetrical the method. This means that if we calculate K_f from K_i and then return to K_i on the basis of the K_f obtained, we end up with a K_i which is closer to the initial value.

Example : If $K_i = .9$, $t_i = 10^\circ\text{C}$ and $t_f = 15^\circ\text{C}$

the value of K_f transferred with a 5°C step is .90723

and the return to the initial conditions gives $K'_i = .90056$,

i.e. a difference of .06% .

The same transfer with an iteration step of 0.1°C gives
 $K_f = .90696$ and $K'_i = .90001$, i.e. a difference of .001% .

2.5.2 Transferring in pressure

The basic principle is that the function $K(p,t)$ can be expressed in the form (see equation (6) in section 2.3) :

$$K(p,t) = 1 + A t + B (p-1.01325) + C (p-1.01325)^2$$

where : $A=2.8E-5$

$C=2.0E-6$

Parameter B, the only unknown quantity in this expression, is determined through the known value $K(p,t)$.

I.e. for the transfer of $K_i(p_i,t)$ to $K_f(p_f,t)$:

$$B = (K_i - (1 + A t) - C (p_i - 1.01325)^2) / (p_i - 1.01325)$$

It is now possible to calculate $K(p_f,t)$

This calculation method is a non-linear interpolation between the starting point and the value of K at normal pressure and at temperature t. Care must be taken for extrapolation when the initial pressure is lower than final pressure.

2.5.3 Combined transfers (pressure-temperature)

It is important to remember that the method for transfer in temperature is only valid at high pressure, ideally around 50 bar abs. Consequently, the transfer of conditions p,t to conditions p',t' is organized as follows :

1: p,t ---> $50,t$

2: $50,t$ ---> $50,t'$

3: $50,t'$ ---> p',t'

A computer program for this procedure, written in "Fortran", is given in appendix A.

2.5.4 Accuracy of the transfer method

The different mean coefficients in the transfer formulae were fitted on the basis of the compressibility factor tables for some fifteen gases of extremely different compositions. The compressibility factor of these gases was measured in laboratory at various pressures and temperatures with an accuracy better than .1%.

The reason the temperature transfer has to be done at high pressure is that all the compressibility factors used to fit the equation were given for pressures between 40 and 70 bar which corresponds to .8 and .94 for the compressibility factors of those natural gases.

These gases cover a very wide range of compositions : N₂ from 0% to 15%, CO₂ from 0% to 5%, C₂H₆ from 0% to 9%, etc.

From the measured compressibility factors at 50 bar and 15°C, K factors were generated, within a pressure range of 0 to 50 bar and a temperature range of 0°C to 25°C, using the transfer method.

None of the transferred K values deviates by more than .1% from its experimental value.

Furthermore, in most cases an extrapolation to 60 or even 70 bar does not give rise to any errors greater than .1 %

The method was also tested for gases containing over 25% nitrogen or 25% CO₂. The .1% threshold is only crossed at the limits of the temperature range , i.e. towards 0 °C or 25 °C. Anyway, errors at these temperatures are lower than .2% if the pressure does not exceed 50 bar abs.

Composition

N2	CO2	CH4	C2H6	C3H8	i-C4H10	n-C4H10	NEO-C5H12	i-C5H12	n-C5H12	C-C5H10	iCS	O2	HE
13.93	.900	81.48	2.899	.396	.869	.079	.008	.020	.020	8.000	.072	0.000	.048

Pseudo-critical pressure = 44.66 Bar

Pseudo-critical temperature = -85.01 °C

Z_c = .99770 Z_{ref} = .91385

T	0		5		10		15		20		25	
0	1.0023	.24E-06	1.0023	-.98E-05	1.0023	-.86E-05	1.0023	.33E-05	1.0023	.24E-04	1.0023	.54E-04
10	.9796	.18E-04	.9910	.13E-03	.9923	.26E-03	.9935	.35E-03	.9846	.44E-03	.9856	.52E-03
20	.9573	.86E-04	.9601	.28E-03	.9620	.42E-03	.9652	.54E-03	.9675	.65E-03	.9696	.75E-03
30	.9354	.21E-03	.9397	.38E-03	.9430	.46E-03	.9475	.55E-03	.9510	.64E-03	.9542	.74E-03
40	.9138	.39E-03	.9197	.48E-03	.9253	.38E-03	.9304	.37E-03	.9351	.48E-03	.9394	.48E-03
50	.8925	.63E-03	.9002	.39E-03	.9073	.17E-03	.9138	.00E+00	.9190	-.76E-04	.9252	-.38E-04
60	.8716	.93E-03	.8811	.33E-03	.8899	-.18E-03	.8979	-.58E-03	.9052	-.81E-03	.9117	-.84E-03
70	.8511	.13E-02	.8625	.23E-03	.8728	-.68E-03	.8825	-.14E-02	.8911	-.18E-02	.8989	-.19E-02

fig 1 : Relative deviation between measured K and transferred K for a Slochteren gas.

Composition

N2	CO2	CH4	C2H6	C3H8	i-C4H10	n-C4H10	NEO-C5H12	i-C5H12	n-C5H12	C-C5H10	iCS	O2	HE
2.434	1.779	87.97	5.552	1.512	.186	.306	.083	.059	.064	.003	.091	0.000	.041

Pseudo-critical pressure = 46.27 Bar

Pseudo-critical temperature = -71.38 °C

Z_c = .99700 Z_{ref} = .88375

T	0		5		10		15		20		25	
0	1.0030	.71E-04	1.0030	.62E-05	1.0030	-.45E-04	1.0030	-.82E-04	1.0030	-.11E-03	1.0030	-.12E-03
10	.9733	-.54E-03	.9751	-.39E-03	.9768	-.26E-03	.9784	-.14E-03	.9799	-.27E-04	.9813	.05E-04
20	.9437	-.94E-03	.9475	-.64E-03	.9509	-.39E-03	.9542	-.16E-03	.9573	.51E-04	.9601	.26E-03
30	.9143	-.11E-02	.9208	-.74E-03	.9254	-.43E-03	.9304	-.15E-03	.9350	.13E-03	.9392	.42E-03
40	.8851	-.18E-02	.8929	-.67E-03	.9001	-.37E-03	.9069	-.98E-04	.9131	.20E-03	.9189	.54E-03
50	.8560	-.63E-03	.8659	-.41E-03	.8752	-.21E-03	.8837	.00E+00	.8917	.27E-03	.8989	.63E-03
60	.8271	.59E-04	.8392	.53E-04	.8505	.67E-04	.8610	.14E-03	.8706	.34E-03	.8794	.69E-03
70	.7983	.11E-02	.8128	.74E-03	.8262	.47E-03	.8386	.34E-03	.8499	.61E-03	.8603	.71E-03

fig 2 : Relative deviation between measured K and transferred K for an Ekofisk gas.

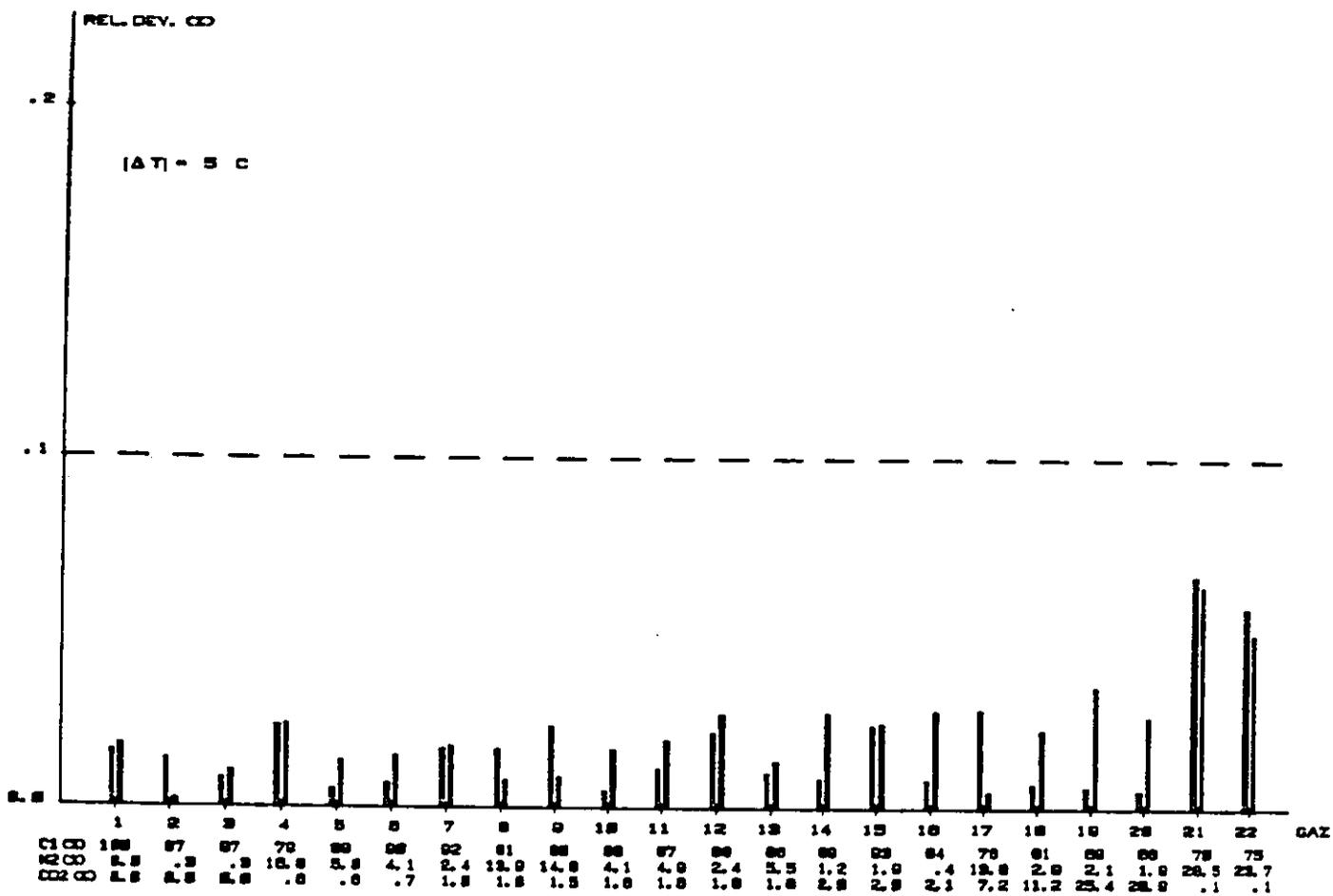


fig 3: 5 °C transfer errors at 50 bar.

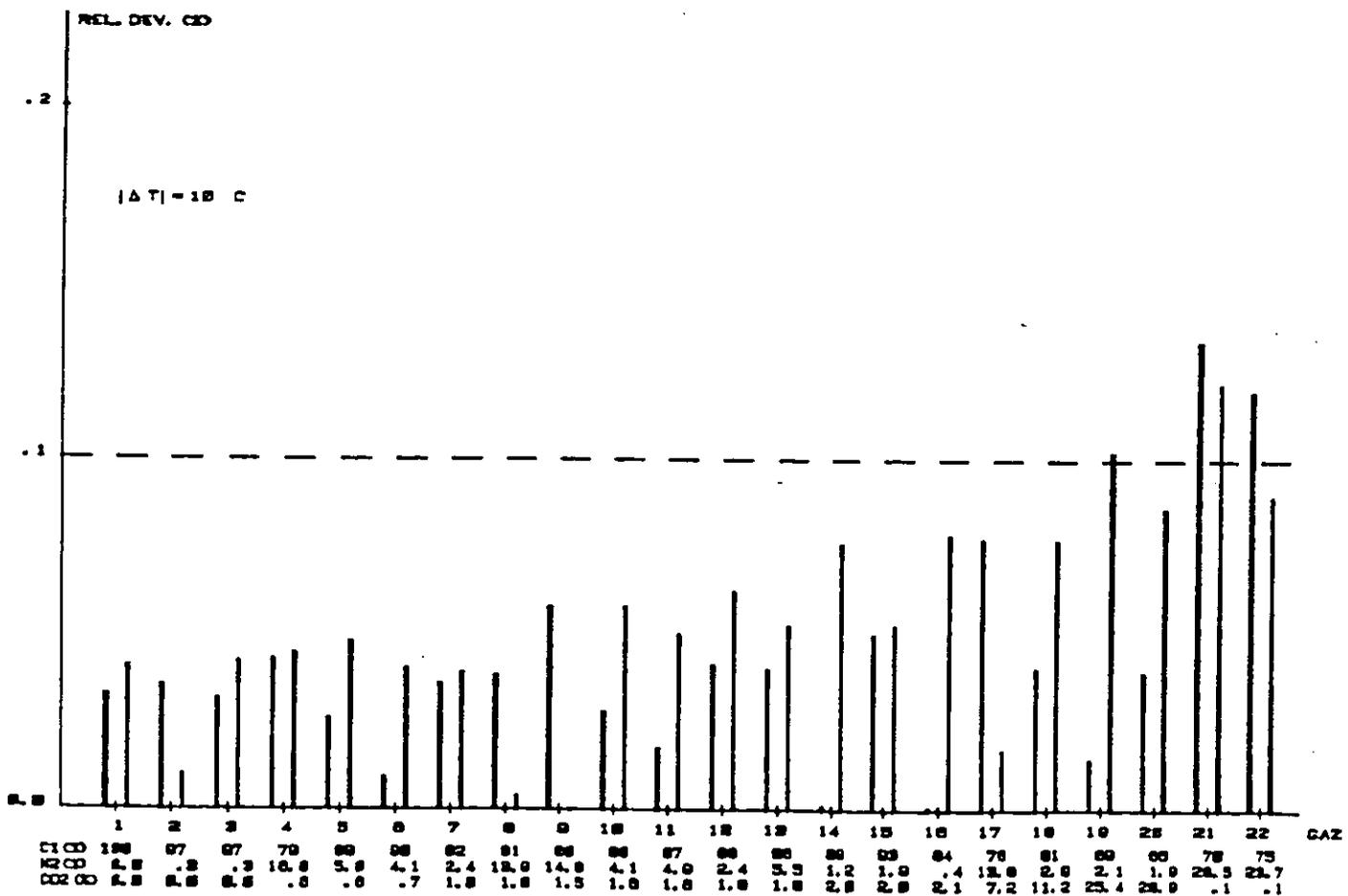


fig 4: 10 °C transfer errors at 50 bar.

2.5.5 Physical interpretation of the transfer methods

The validity of the transfer methods for natural gases differing considerably in composition is so surprising that we tried to find a physical explanation.

Due to the "principle of corresponding states", we know that the function of state of all gases is identical if it is expressed in term of reduced temperature and pressure, i.e. the pressure or temperature quotient with the pseudocritical pressure and temperature of the gas. An examination of the critical pressures of the various components of natural gases shows that they are extremely similar, with the exception of CO₂.

This explains the low variation from one natural gas to another of the $2 \cdot 10^{-6}$ curvature coefficient of the K function expressed on an isotherm. This allows K to be transferred in pressure by non-linear interpolation between the two values, one of them being the K value at base pressure, which can be accurately estimated for all natural gases.

The explanation for the good performance of the transfer method for temperature is different. The critical temperatures of the natural gases components are more different than their critical pressures.

They are not, therefore, in a "quasi-corresponding" state on an isobar.

The value of the compressibility factor of these gases at 50 bar, for example, is then an indication of the non-corresponding state at this pressure. It therefore shows in which "part" of the general equation of state this gas takes place for this pressure. It is not surprising, therefore, to find a link between the local value of the K factor and the local variation of this factor with respect to the temperature. This linear relationship allows transfer in temperature.

The principle of corresponding states being only an approximation, it is logic that the transfer method performs well only within a limited pressure and temperature range.

3 INSTALLATION OF THE Z-METER IN TURBINE METERING STATIONS

3.1 Installation Conditions

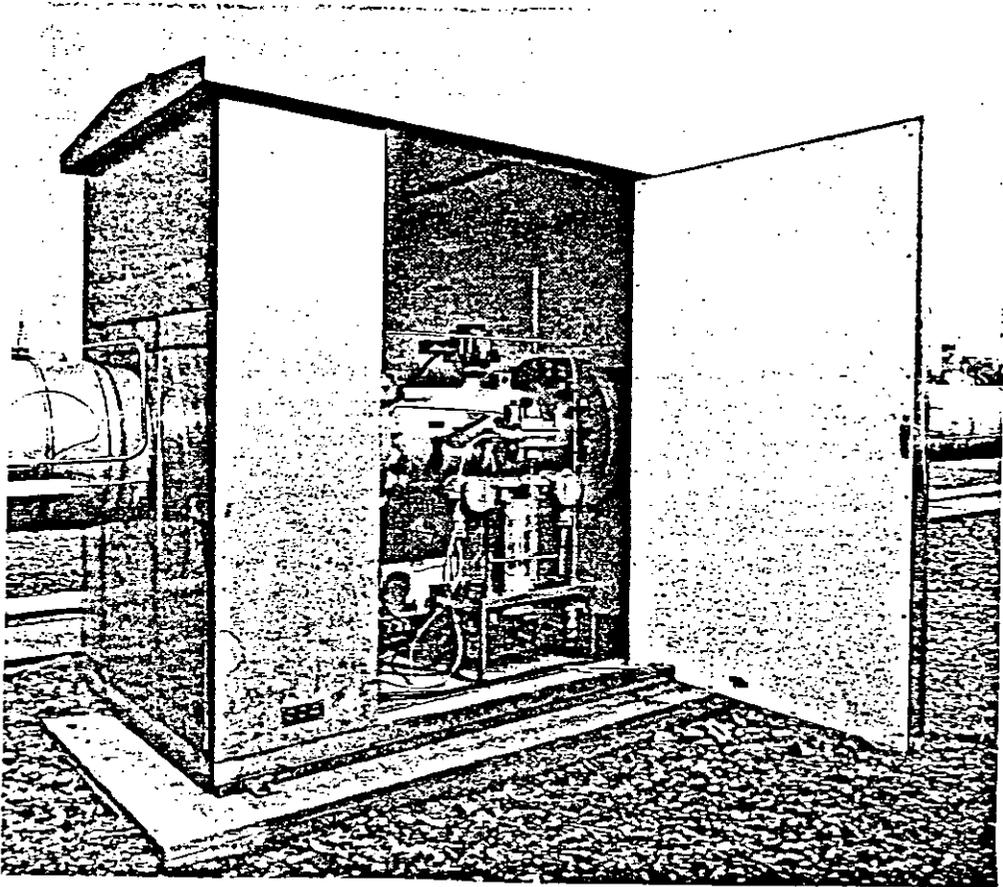


fig 5.

The Z-meter is installed close to the turbine meter, in a small aluminium cabin enclosing the meterrun. The cabin, including a wooden floor, is thermal insulated. The gas pipe acting as an exchanger, the temperature in the cabin is kept close to that of the gas. Usually, the difference is lower than 5°C . Features of this installation are the good shielding of the turbine meter mechanical index and the ease of its dismantling for meter removal.

3.2 Installation Equipments

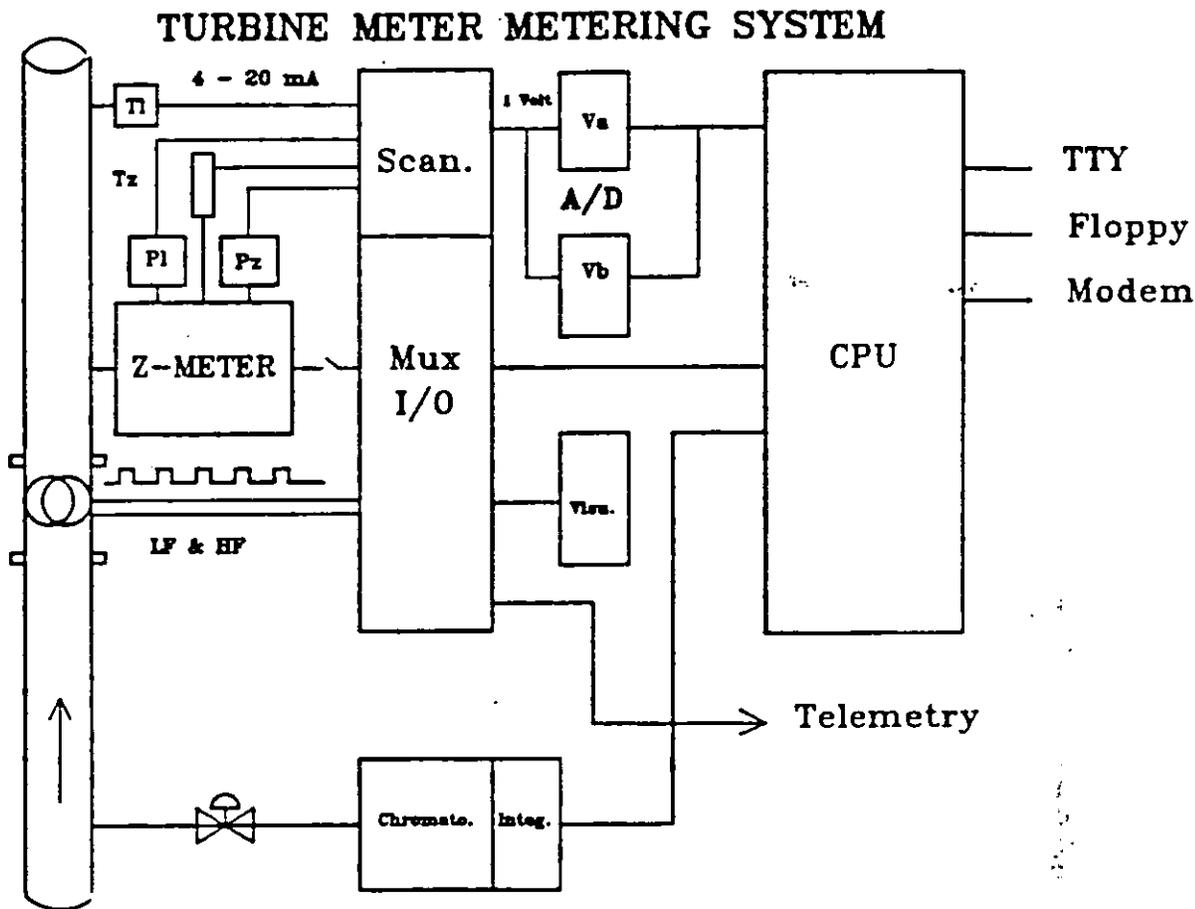


fig 6

3.2.1 Computer Equipment

The metering systems of Distrigaz are equipped with Hewlett-Packard 21 MX series minicomputers of which "RAM" memory has a capacity of 64 kbytes . All the software has been written at Distrigaz in Assembler. Mini-floppy diskettes with a capacity of 130 kbytes are used to store the "program code", the parameters qualifying the installation and the metering results. A printer-console allows man-machine communication to

change, for example, some metering parameters and prints out all the metering results and the various events of the metering station. The Hewlett-Packard 6940B multiprogrammer has various functions, such as the turbine meter pulses counting, the pressure and temperature transmitter channels scanning, analog outputs, digital in- and outputs, etc. The voltage and resistance measurements are made by two parallel multimeters of the type HP 3455A or Fluke 8840A of which accuracy is better than .01 % .

3.2.2 Pressure transmitters

The pressure transmitters are manufactured by Rosemount. They produce an analog output of 4 - 20 mA. The current is converted into a voltage of .2 to 1 V by a 50 Ohms, .005% precision Sfernice shunt.

Their range is adapted to suit the metering conditions. As it is described in section 2.4.1., the Z-meter absolute transmitter, of which nominal span is 0 to 7 bar abs., is reduced to .8 to 3 bar abs. . For line pressure measurements, the most currently used transmitters have a 0 to 70 bar nominal range which can be adapted for higher pressures.

The transmitters are calibrated in the laboratory. It consists in calculating the voltage second degree polynomial expressed in "points" (volts multiplied by 1.E+5) as close as possible, in the "least squares sense", to the pressure/voltage couples:

$$p = a + b V + c V^2$$

Later on, the transmitter will never be altered again. The adjustment potentiometers are permanently sealed. If recalibration was necessary, only coefficients a, b and c will be changed. This policy allows to trace the transmitter history more efficiently.

The pressure standards are those described in section 2.4 .

The accuracy of the transmitters given by the manufacturer is +/- 0.25% of the calibrated span at the temperature of the calibration. But the study that we have undertaken about the temperature behaviour of some ten transmitters has revealed some significant deviation of several "per thousand" with twenty degrees increasing or decreasing. The results are however within the manufacturer specifications.

The deviation is mainly a zero shift, the curves being parallel to themselves. This fact is very important. As we shall see further on, for the specific use of the transmitters with the D&H Z-meters, a zero shift has no significant influence on the Z measurement. Care must be taken for line pressure transmitters whose accuracy is directly affected by a shift in temperature. The transmitters chosen by Distrigaz are selected by Rosemount for their stability in temperature. Their temperature behaviour is now systematically studied in our laboratory and the maximum zero deviation that is tolerated on a 20°C range is .2% .

As we shall see further on, this deviation is of little importance for the correction factor determined by the Z-meter, but has a great influence on the accuracy of "reference Z".

3.2.3 Temperature transmitters

The temperature transmitters are manufactured by Degussa. They produce a signal of 4 to 20 mA for a range of -10 °C to +35 °C.

The transmitters are calibrated in the laboratory from 5 to 35°C . The output current is converted into a voltage of .2 to 1 V by a 50 Ohms, .005 % precision Sfernice shunt. The standard is a Pt 100 resistor of which resistance at 0°C has been previously determined by the method described in section 2.4.2 . It is used only in the laboratory as transfer standard . Calibration consists in calculating the voltage first degree function for the temperature, the voltage being expressed in terms of "points" (volts multiplied by 1.E+5), fitting the calibration points by the least squares method. Each transmitter is therefore qualified by two coefficients :

$$t = a + b V$$

The accuracy on the temperature measurement is always better than $.1^{\circ}\text{C}$.

3.2.4 Turbine flow meters

The recent introduction of several high pressure natural gas calibration rigs enables the use of turbine meters for high precision metering installations. Some of our meters have been tested on three or even four calibration facilities working at various pressures between 8 and 62 bar. More often than not, the results show accordance between the different curves within half a per cent. Modern calibration laboratories, on the other hand, claim an absolute accuracy of $.3\%$. We think, therefore, that using any curve established above 8 bar by one of these laboratories should guarantee an absolute accuracy of about $.5\%$.

The accuracy on the discharge coefficient, used for orifice metering, is of the same level. At the present time, there is no clear advantage in using one method rather than the other.

However, the lower installation cost, shorter and more accurate instrument chain, the greater rangeability and the recording of gross volumes by a mechanical counter without electric power, give turbines the advantage over orifices.

In order to derive maximum benefit from the intrinsic qualities of turbine flow meters, the installation should be standardized. We are thinking here of the straight sections before and after the meter and the use of a flow straightener.

Research is underway in this field (draft ISO Standard in discussion in the TC 30 committee) .

Through the lack of any standardization, the normal installation conditions at DISTRIGAZ are as follows :

- conical filter and "Sprenkle" type straightener, at 5 diameters after the inlet valve
- straight section in front of the meter : 15 diameters
- straight section after the meter : 7 diameters
- heat-insulation of total meterrun.
- pressure (or the compressibility coefficient) measured at the "Pr" connection of the meter;
- temperature is measured downline, after the 7 diameters of straight section.

Recently, upon the request made by Distrigaz, the manufacturer "Instromet" has integrated the temperature transmitter in the turbine meter itself. Three of these meters are used now in Zeebrugge and show very good performances (differences between the temperatures measured on three parallel lines are always lower than $.1^{\circ}\text{C}$). This will perhaps allow in the future reducing of the meterrun insulation. A study will be carried in this respect.

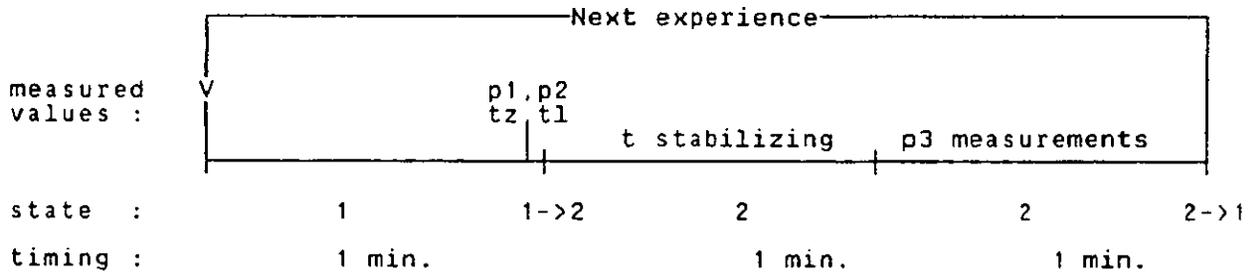
Preferably, the turbine meters generate two independent signals :

- A low frequency signal "LF" (< 1 Hz) from the meter index.
- A high-frequency signal "HF" ($< 1,500$ Hz) from the vanes of the turbine impeller picked off by a proximity detector.

The LF and HF pulses accumulate in electronic counters of 4 and 8 bits respectively . Preferentially, the computer uses the HF channel for metering. This is the shortest chain as the signal is generated directly by the vanes of the meter. In addition, the higher frequency level gives a better resolution for calculation of the instantaneous flow rate of the installation. If there is a problem with the HF signal, its disappearance in particular, the computer switches to the LF signal to continue the metering.

3.3 Z-meter measuring cycle

The Z-meter is a cyclical apparatus. The absolute pressure measured by the transmitter has not the same significance at every moment.



When the apparatus is in state 1, the measured pressure is the barometric pressure, p_2 . This value, the line pressure p_1 , the temperature of the gas in the Z-meter t_z and in the line t_1 are memorized by the computer just before the Z-meter passes to state 2.

Passing to this state, the gas at pressure p_1 imprisoned in the small volume, is expanded and fills both volumes. The gas temperature decreases in the small volume and increases in the large one. The thermal exchange will stabilize the temperature after about one minute, as proved by a stable pressure p_3 . The gas temperature has become that of the metal mass and is practically identical to that of the gas before expansion (difference lower than $.02^\circ\text{C}$).

The computer memorizes the values of p_3 measured during the following minute and uses the average. No deviation of more than $.01\%$ between the extreme values is tolerated. Otherwise, this would indicate a leak from valve a (inlet) or valve c (exhaust), depending whether pressure p_3 is increasing or decreasing.

After this and other, mainly boundary tests, for example p_2 must be between $.8$ and 1.2 bar, the computer calculates the $K(p, t_z)$ factor.

The timing of one complete Z-meter cycle is 3 minutes.

3.4 Reference Z

"Reference Z" means the compressibility factor K at reference conditions : $p = 50$ bar and $t = 15^{\circ}\text{C}$.

The value of 50 bar was chosen because it is close to the operation pressure of the Z-meter in the large metering stations (between 45 and 55 bar abs.) and it is mostly above the pressure normally wanted for the compressibility factor. The extrapolation will therefore never be too large .

The existence and the reliability of the transfer method described in section 2.5 has made the notion of reference Z possible .

Many reasons have led to the elaboration of this notion :

3.4.1 Asynchronism problem

The flow computer, including a quartz-crystal clock, operates in real time . The computer scans the state of the LF and HF counters of the turbine meter ten times a second . It controls the crossover of the two accumulators and conducts certain validity tests on the data . The result is a gross volume .

Every 10 seconds, the computer calculates the instantaneous volume of the station at base conditions, summing the quantities of gas passing through each meterrun and using the normalization factor in equation (1) .

The calculation is possible if the following procedure is followed. The pressure and temperature of the gas are measured several times during the cycle of ten seconds and averaged . After the 3 minutes Z-meter cycle, the computer calculates the $K(p, t_z)$ factor and determines the "reference K" . This factor is kept in memory and after each 3 minutes, the new measurement replaces the preceding value of reference K .

This factor will be used every 10 seconds to calculate the normalization factor, transferring the reference K to the line conditions .

This notion simplifies the software because only one value is stored and read in the computer memory . Moreover the accuracy on the K measurement is not altered by passing through an intermediate reference K rather than calculating directly the K factor from the initial conditions. This is due to the fact that the differences between the final and initial conditions are :

$$\begin{aligned} | t_f - t_i | &< 5 \text{ } ^\circ\text{C} \\ | p_f - p_i | &< 5 \text{ bar} \end{aligned}$$

For example,

if the values measured after the 3 minutes Z-meter cycle are:

$$p_1 = 61 \text{ bar, } t_z = 9^\circ\text{C and } K = .8419$$

and the values measured at one computer cycle are :

$$p_1 = 62 \text{ bar, } t_1 = 4^\circ\text{C}$$

the value of K directly calculated is .82721 and the value calculated passing through K(50,15) is .82722 .

An important remark is that, due to the fact that the Z-meter cannot be installed inside the meterrun, a transfer of K from the Z-meter temperature to the line temperature is always obligatory even if the temperature and the pressure have not changed during the Z-meter cycle.

3.4.2 Mean K value

A possible use of reference K consists in averaging the compressibility factor measurements daily and/or hourly. This factor, pressure and temperature dependent, should first be brought to reference conditions before an average can be made.

This daily average of reference Z for each gas enables, through the transfer method, the creation of a table of K factors for every

pressure and temperature in the normal range of metering.

In Belgium a natural gas is always qualified by its reference K.

It is important to note that in this case, the pressure p_1 measured by the transmitter must be as precise as possible .

3.4.3 Telemetry

Another possibility is that reference K could be remotely transmitted in digital or analog form to other metering stations. A central measuring station with a Z-meter could update, in this way, the compressibility function for metering stations receiving the same gas .

3.4.4 Intercomparison

If the metering station is equipped with parallel runs and several Z-meters are measuring the same gas, it is possible to compare the different "reference K" and detect a possible discrepancy. It is important to note that this comparison includes the eventual error of the associated line pressure transmitter .

3.5 Z-meter on-site verification.

As it is just hereabove mentionned, a simple check can be made if there are multiple Z-meters measuring the same gas through the comparison of the "reference Z" values .

If a problem with one of the Z-meters has been detected or if there is only one Z-meter, the following method is applied . The valve between the meterrun and the Z-meter is closed and a bottle of pure methane is connected to the entry of the Z-meter . After about five samples, a steady reading of the output is obtained. "Reference Z" of methane is printed out every 3 minutes and can be compared with the

value of the table. This is done at various pressures from 60 to 40 bar.

When in agreement, the verification is terminated. If not, a portable D&H deadweight standard, with an accuracy of about .1%, is used to check the origin of the discrepancy .

If the transmitter is defective, it is replaced by another one which has been previously calibrated in the laboratory. If there is another problem, the Z-meter is send back to the laboratory for a more detailed examination. This will occur, for example, if there is a problem with the absolute pressure transmitter of the Z-meter.

4 ACCURACY OF THE Z-METER

4.1 Intrinsic Z measurements accuracy

The intrinsic accuracy is the basic accuracy obtained in the laboratory for Z or K measurement, taking into account that the precision for the high pressure measurement is lower than .005% if the laboratory is well equipped. Intrinsic accuracy evaluation is based on the following experimental facts : The standard deviation of the A volume ratio determination is lower than .005%. The Z-meter instrument error, within a 95 % confidence level, is then better than .01% in the temperature range for which the Z-meter was calibrated..

To this error shall be added the uncertainty of standard gas compressibility values used to calibrate the Z-meter .

Nitrogen was normally used for this purpose. Other gases such as methane, argon and helium also are utilized. It has to be noted that the compressibility of these gases sometimes differ appreciably. For instance, the helium Z value, practically linear in pressure, is above 1 within the usual pressure range. Thus, it was very interesting to confront the K measurements for helium, methane and argon by a nitrogen calibrated Z-meter with up-to-date tables.

This comparison was carried out at 50 bar and at laboratory temperature (23°C). Obtained results:

Methane : deviation < .01 % .
Helium : deviation < .02 % .
Argon : deviation < .04 % .

The table used for methane is a fit of the Douslin measurements. Recently a new table for methane has been elaborated based on fitting 297 measurement points obtained from the compressibility factors determined by Trappeniers (1979), Douslin (1964), Schamp (1958), Roe (1972) and Vennix (1970) . These points have been used in the creation

of the GERG and GRI "Data Bank". The accuracy of this table is about .02% at custody transfer conditions .

The close agreement between these values and those for nitrogen allows to claim a total .035 % accuracy on Z-meter calibration, i.e. .005% due to the pressure standard, .01% due to the Z-meter itself and .02% due to the standard Z table uncertainty.

We have no information on the real accuracy of the helium table. Its compressibility function linearity, its originality ($Z > 1$) and the remarkable correspondence with the other measurements are a supplementary proof of the Z-meter precision and its independence of the nature of the gas.

4.2 Accuracy as a corrector

This is the fundamental topic as it concerns the use of the Z-meter to determine the p_1/K_1 factor, i.e. the normalization factor except for the temperature measurement.

4.2.1 Uncertainty on the line pressure transmitter

The pressure p_1 is measured at two levels of the calculation process. The ratio p_1/K_1 being determined globally, it will be seen that an error on the p_1 measurement will produce an attenuated error on the ratio itself .

1) The iterative method described in section 2.3 uses successive approximations of K_1 to calculate K_2 and K_3 . K_1 is directly affected by the error on p_1 . The final error on the p_1/K_1 ratio will be around 25 times lower than on p_1 .

If, for example, $A=50$, $T=20^\circ\text{C}$, $p_2 = 1$ bar and $p_3 = 2$ bar the value of K calculated by the iteration method will give $K_1 = .96036$ for $p_1 = 50$ bar and a ratio p_1 / K_1 equal to 52.0638

A 1% error on the line pressure , i.e. $p_1 = 50.5$ bar will give $K_1 = .97036$ and a ratio equal to 52.0425, i.e. a difference of .04% .

2) The other use of the separate p_1 is due to the discontinuity of the Z-meter measurements. As it has been seen in the section "Reference Z" , the p_1/K_1 factor is measured "globally" only every 3 minutes .

The pressure variation between the moment "t" when p_1/K_1 is measured and moment "t'" when normalization factor is calculated has to be taken into account. Only the pressure transmitter drift between two successive Z-meter measurements would have any significant effect on the accuracy of the p_1/K_1 factor within the normalization factor .

A numerical example will illustrate this :

Let us suppose that at moment "t" the conditions are those of the previously example : $p_1 = 50$ bar, the corresponding K_1 factor is .96036 and the accuracy of the Z-meter is infinite.

Supposing the pressure transmitter at that time has drifted and indicates 50.5 bar, the K_1 factor calculated from this pressure will be .97036 . Of course, it is directly affected by the pressure error.

Considering moment "t'". The exact pressure at this time is, for example, 51 bar and the K_1 factor, which is calculated from $K(50,15)$ using the transfer formula, is .95964 . The exact p_1/K_1 ratio at this instant is then 53.1449 .

The measured pressure will be 51.50 bar . As the interval (t'-t) is small, the transmitter error shall be practically the same as at instant t.

Calculating the K_1 value at 51.5 bar from the value of this factor at 50.5 bar gives .96985 . The calculated p_1/K_1 ratio is then 53.1010 .

The difference relative to the real factor is .08 % .

In this simple example a 1 % error on the p_1 measurement has affected the p_1/K_1 ratio only by an error 12 times lower.

In addition to the function as a "Z-meter", it was demonstrated that this instrument considerably reduces the impact of the line pressure error.

4.2.2 Inaccuracy on the Z-meter pressure transmitter

As shown in equations (4) and (5) of the section 2.2, p_2 and p_3 values are very important in the determination of the Z factor by the Z-meter.

As indicated above, the basic accuracy of this apparatus is better than .1 % . Experience with about twenty such instruments used in metering stations shows that this precision is maintained for several years without absolute pressure transmitter recalibration.

All the checks carried out have proved that measuring errors were always within .1 % .

This accuracy and metrological stability seem paradoxal considering the industrial specifications of the transmitters used.

In fact, it is not a miracle at all. The results are explained by a critical examination of equations (4) and (5).

In equation (5), ratio A is about 50, K_2 is about 1 and K_3 is around .998. The second part of the equation is roughly :

$$51.10 \frac{p_3}{3} - 50 \frac{p_2}{2}$$

As p_3 and p_2 are measured by the same transmitter, it is evident that any zero drift does not significantly affect the value of the

equation, i.e. K_1/p_1 . A short calculation shows the attenuation factor is at least 25.

Considering the particularly suitable conditions for the device installation, no zero deviation above 5 mbar has ever been observed. Such a deviation would only give .01 % error on p/K .

5 CONCLUSION

Our experience of several years prove that the Z-meter is a sturdy and reliable instrument . More than five hundred thousand expansions are currently carried out before a leakage problem of the valves can appear.

This apparatus is not fundamental, but calibrated with a gas which characteristics are known, it allows the measurement of the compressibility factor of any gas.

Thanks to its speed, it can be used in sequence in any process including gas flow measurements. Moreover, if the gas composition is variable, it is the ideal corrector to normalize the gas flow rate measured in turbine metering systems. Its accuracy on the P/K measurement is always better than .1% .

APPENDIX A Z-TRANSFERRING PROGRAM:

```

PROGRAM TRANZ,REV 27.01.84

C
C *****
C *
C * This program is used to compute K(PF,TF)
C * from K(PI,TI) .
C *
C * The iteration step is about .01 °C
C *
C * Test values:      TI=15 PI=50 KI=.9000
C *                   TF=0  PF=25 KF=.9379
C *
C *
C * !!!!!!! ONLY VALID FOR Z/Zn (K)      !!!!!!!
C *****
C
C Main Program
C -----
C LU=1
C WRITE(LU,1000)
C READ(1,*)TI,TF,PI,PF,ZKI
C
C I are initial conditions
C F are final conditions
C
C From K(PI,TI) to K(50,TI)
C -----
C PPF=50.
C CALL TRPRES(TI,PI,PPF,ZKI,ZKF,B)
C ZKI=ZKF
C IF(TI.EQ.TF)GOTO 200
C
C From K(50,TI) to K(50,TF)
C -----
C DELT=TF-TI
C IH=ABS(INT(DELT*100))

```

```

      HH=DELT/IH
      DO 1 I=1, IH
      CALL TRTEMP(HH, ZKI, ZKPF)
1     ZKI=ZKPF
C
200  CONTINUE
C
C     From K(50,TF) to K(PF,TF)
C     -----
      PPI=50.
      CALL TRPRES(TF, PPI, PF, ZKI, ZKF, BB)
      ZKI=ZKF
C
      WRITE(LU, 1200) PF, TF, ZKI .

1000 FORMAT(2X, "ENTER THE FOLLOWING DATA:", /, 2X,
+ "TI, TF, PI, PF, K(PI, TI)", /)
1200 FORMAT(2X, "Value of K(p, t) for P=", F6.2, X, "bar"
+ , X, "and T=", F6.2, X, "DEG.", X, "is:", F7.4)
      END
C
      SUBROUTINE TRPRES(T, P1, P2, ZK1, ZK2, BP)
C     -----
      DATA AP, CP, PREF/2.8E-5, 2.E-6, 1.01325/
      PE1=P1-PREF
      PE2=P2-PREF
      BP=(ZK1-1-AP*T-CP*PE1*PE1)/PE1
      ZK2=1+AP*T+BP*PE2+CP*PE2*PE2
      END
C
      SUBROUTINE TRTEMP(PAS, ZK1, ZK2)
C     -----
      DATA AT, BT/1.8584E-2, -1.8864E-2/
      ZK2=ZK1*(1+(AT+BT*ZK1)*PAS)
      END

```

ON-LINE VALIDATION OF DENSITOMETERS
BY PRESSURE PYKNOMETRY

Co-Authors Charles L.H. Johnson and Heather Fitzgerald
Moore, Barrett and Redwood Ltd.

INTRODUCTION

In a Mass transfer accounting system the measurement of the density of the fluid is of equal importance to the measurement of the volume of fluid transferred. It is therefore of equal importance to have the capability to check the calibration of on-line density meters as it is to prove the volumetric meters and to calibrate the master provers.

Since all density measurement devices in the North Sea rely on the variation in fundamental frequency of vibration of a tube or vane with changing density it is important to have an independent means of determining the fluid density. High pressure Pyknometry provides such a method fundamentally different from that used on-line.

Using purpose built, mobile, pyknometry systems, Moore Barrett and Redwood have carried out the validation of densitometers calibrations on Fiscal systems throughout the North Sea. The method has also been used successfully on crude oil, condensate, NGL and petroleum products.

This paper reviews the progress in equipment design and construction and improvements in the methods of obtaining repeatable and representative results under adverse conditions. It also reviews the method of pyknometer calibration adopted by MB+R which allows the overall uncertainty of the method to be reduced.

SUMMARY OF METHOD

To validate the calibration of a density meter at its operating conditions by pyknometry, a sub-sample of the fluid passing through the densitometer must be captured within the pyknometer. Co-ordination of the sampling and the reading of the densitometer must be precise.

Conditioning of the pyknometers to line conditions of temperature and pressure are of the utmost importance. Therefore accurate measurement of pressure and temperature within the conditioning skid are important.

As the density meter sees only a small portion of the total fluid in the main line and the pyknometer captures a small sub-sample of the fluid flowing through the densitometer, the importance of representative samples within the pyknometers cannot therefore be overstressed.

The filled pyknometers are removed to a suitable site laboratory where the outside surfaces are thoroughly cleaned and dried. The pyknometer is then weighed. Having previously determined the weight of the empty pyknometer at local conditions, and knowing the internal volume and expansion coefficients for the pyknometers, the density at line conditions can be calculated.

EQUIPMENT

The original equipment designed and built by Stanhope Seta for the sample conditioning was envisaged to be permanently sited on a platform or installation metering station. In order to render it portable considerable redesign of the pipework had to be undertaken. Consideration had to be given to the weight of the cabinet and the pipework and supports within.

In order to minimise heat loss between the line connections and the pyknometers all the pipework and hose connections are lagged. The internal pipework is valved so that the system can be flushed with fluid without contaminating the pyknometers. This is particularly useful on initial start-up of an exercise when the sample point is first opened.

The by-pass system also allows the pyknometers to be isolated from the main flow to facilitate draining of the internal pipework to allow easy disconnection of the Hanson couplings. In the case of high pressure NGL systems the drain system doubles up as a means of pressurising the pyknometers with inert gas to avoid chilling from flashing of the NGL.

Monitoring of the temperature across the system is carried out by means of a PRT upstream of the pyknometer and two temperature shoes fitted into the lagged, insulated pyknometer carry case which contact the skin of the pyknometers. The temperature across the system must balance to within 0.5 deg C.

Pressure gauges are connected to 3 points across the system to ensure that line pressure is achieved at the time of closing the outlet valve when sampling. Flow through the pyknometers is monitored by a variable area flow meter.

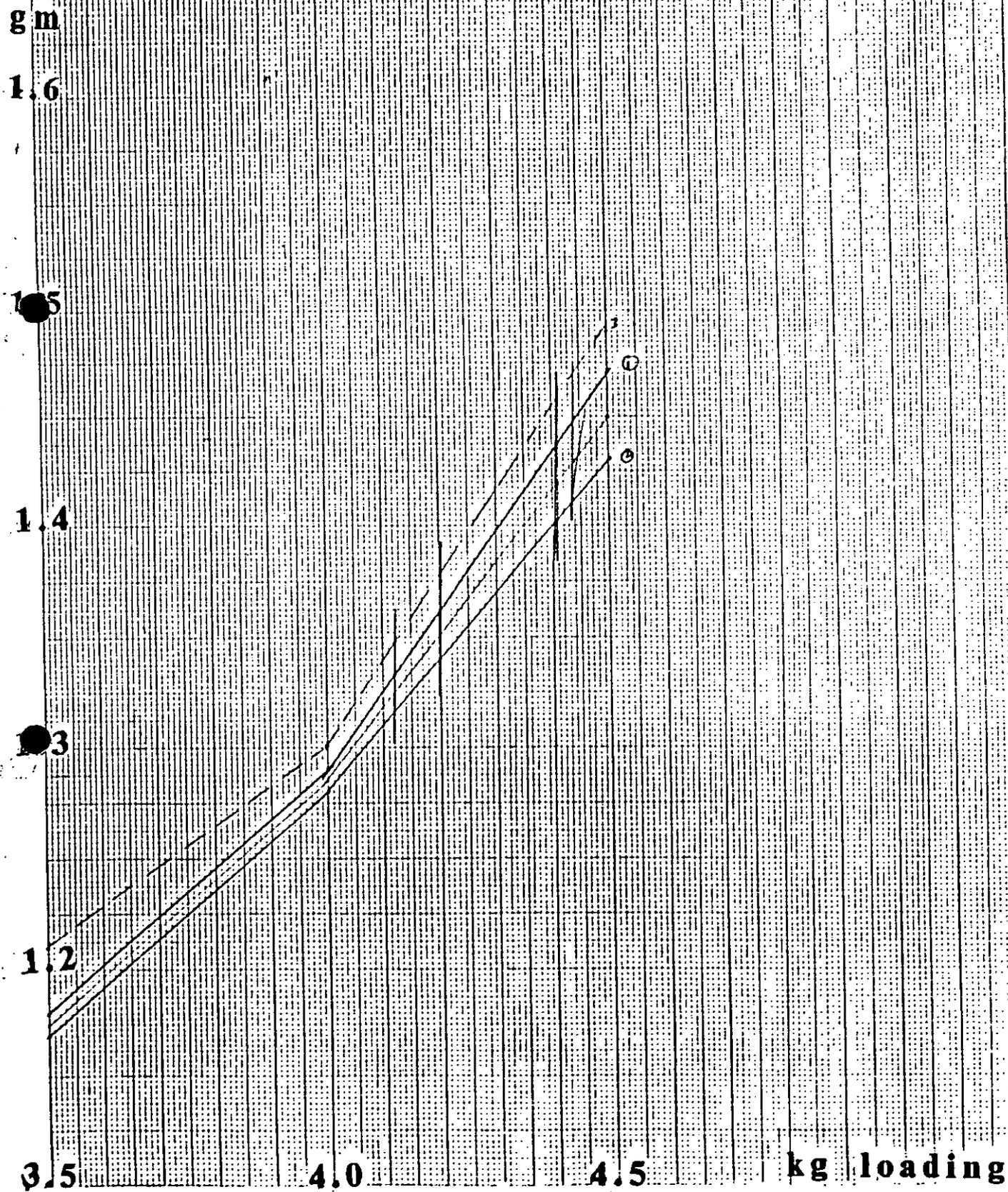
The balance used on site to weigh the pyknometer is a Sartorius MP 1507 Electronic balance fitted with the "Animal Weighing Program". This software is able to compensate for the vibration and motion of the platform and produces weights accurate to the desired 0.01g.

Since local conditions vary from place to place, the weights of the pyknometers, full and empty, are referenced to a series of masses which have been certified by a UK recognised National Calibration Laboratory. It has been found that these electronic balances exhibit nonlinearity in the range 3.5 kg - 5.0 kg. This is especially relevant on offshore platforms when vibration and motion are exaggerated.

To compensate for this lack of linearity a series of weights at 3.5 kg, 4.0 kg and 4.5 kg are plotted against the load difference. This permits the correction of the full and empty weights of pyknometers to be applied accurately. All calculations can be performed on a standard base.

The graph below shows the extent of this non-linearity.

BALANCE NON-LINEARITY



SAMPLING

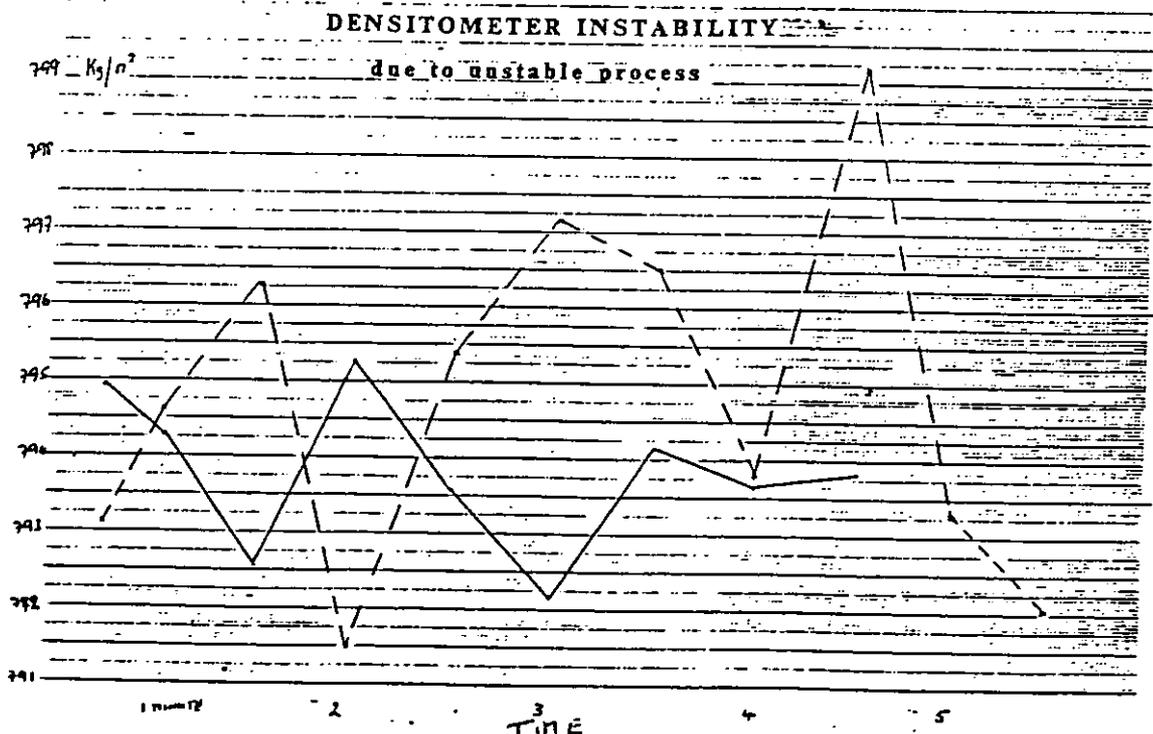
The technique of obtaining representative samples in the pyknometers, under line process conditions, can be an art form. The co-ordination of density meter readings and the catching of samples are the most important factors in validating the calibration of the density meters.

A complete understanding, by the personnel performing the validations, of the engineering and laboratory procedures used in obtaining density measurements is imperative if accurate and meaningful results are to be obtained. This level of understanding provides an overall degree of certainty that the complete density measurement system is being assessed and not just the performance of the densitometer tubes.

Pyknometry is therefore providing a means of validating the the total density measurement system, the temperature and pressure measuring devices, the flow computer/density convertor and the densitometer device. It also gives the assurance that the positioning of the ancilliary equipment in the system gives the most accurate and representative measurements of temperature and pressure in the system at the densitometer. It is current usual practice to use values obtained from the main line or the volume metering lines for the calculation of line densities.

Stability of process conditions is important to the successful validation of densitometers. The IP Code of Practice used as guidelines requires stability of process density to be better than 0.05% over 2 minutes. In installations where it is not possible to obtain this stability, plots of the density against time must be used to obtain the density at the exact time of sampling.

The graphic examples below illustrate the methods of relating line density to the pyknometer density under unstable conditions.



Where the conditions of line density are stable an average of the density over the two minutes prior to the sampling can be used as representative of the density of the fluid in the pyknometer.

Flow rate through the pyknometers is critical in obtaining duplicate samples representative of the fluid. This is particularly true of NGL systems and where there are crudes with high water contents, there is a tendency for the heavier components to accumulate within the pyknometers at low velocities.

The IP code requires duplication between pyknometers better than 0.05% for the determination to be acceptable. In practice it is found that, with experience, duplication of better than 0.02% can be achieved for crude oil. For NGL and condensate systems this level of duplication is more difficult to achieve and the 0.05% is more realistic.

Experience has shown that NGL and condensate homogeneity systems offshore pose considerably greater problems due to the non homogeneity of the fluid, when glycol or other contaminants are present. The ability to achieve duplication is adversely affected by this and the achievement of duplication better than the 0.05% is therefore more difficult.

The accumulation of the heavier components in the pyknometers is a function of the flow rate obtainable. This has an effect on the representativity of the sample and hence on the validation of the density meters. By controlling the flow rate and the length of time to achieve temperature stability it is possible to minimise the effect on some systems and eliminate it on others.

Calibration of Pyknometers

The procedures, developed by Moore, Barrett and Redwood, for calibrating the base volume and mass of the pyknometer follow closely the original calibration procedures of NPL and those proposed in API Chapter 14.6.

The mass of the pyknometer body and of the valve components are determined independently using a specially modified bullion balance and a Sartorius research grade balance to 0.1 mgm. The pyknometer is reassembled and weighed, the total weight should agree to within 0.5 mgm of the total of body and fittings weights.

The initial volume at base conditions and the coefficients of expansion due to pressure and temperature are determined using water. Base volume at 25 deg C and 1 bar A is determined. Further volumes at elevated pressures of 10, 20, 60 and 120 bar are determined to establish pressure coefficients. Volumes at 5 deg C and 50 Deg C are determined at constant pressure to establish temperature expansion coefficients.

Thermometry is carried out using an ASL F26 bridge fitted with a Rosemount 100 ohm platinum resistance sensor and a Cropico 100 ohm standard. A Tinsley 5187 SA 25 ohm sensor complete with 30 ohm standard is currently undergoing calibration at the National Physical Laboratory, and when this is brought into use they should allow temperature measurement with uncertainties of the order of +/- 2mK and produce a subsequent improvement in all the volumetric uncertainties quoted below.

A Budenberg 380L dead weight tester with a stated accuracy of 0.04% along with a Fig 28 oil seal is used. The manufacturers state that the error introduced by the oil seal is no greater than 0.014 bar at any applied pressure

Weighing is carried out on a purpose-built bullion balance with a total capacity of 5kg and a nominal sensitivity of 2 mg per division. Weights up to and including 100 g are of E2 standard, above 100 g, are of F1 standard, but have been recalibrated using several sets of E2 weights to achieve uncertainties similar to E2 standard.

Valve plugs and fittings are weighed on a Sartorius research grade balance with has a resolution of 50 microgrammes at this load.

All weighings are carried out using Gauss's method, and air buoyancy corrections are always applied. Air densities are calculated from air temperature, pressure and humidity observed during the weighing.

All water used is drawn from a Barnstead water purifier, which gives a quality exceeding 18 Megohm centimetre resistivity or 0.055 microSiemen per centimetre conductivity.

Water densities at temperature and pressure are taken from Kell, Journal Chemical and Engineering Data Vol.20 No. 1 (1975).

We currently believe our uncertainties to be as follows:

Mass of pyknometer body	+/- 7mg.
Mass of complete pyknometer	+/- 7mg.
Base volume	+/- 0.02 ml
Change with pressure	+/- 0.0002 ml/bar
Change with temperature	+/- 0.001 ml/deg C

Using state of the art thermometry and pressure control equipment and a balance capable of weighing to mgms it is possible to reduce the uncertainty of calibration on each pyknometer to 0.004%.

Uncertainty

Practical experience, by Moore, Barrett and Redwood, shows that the uncertainty of performing the pyknometry exercise in the field is 0.013%. For duplicate pyknometers this uncertainty is 0.010% under field conditions. This takes account of the weighing uncertainty and that of the pressure and temperature measurement devices.

To ensure that any systematic uncertainty associated with the calibration of individual pyknometers is minimised we use random pairings of the pyknometers during an exercise. In this way any systematic error in a pyknometer is made obvious to the operator and can be investigated. The tight control of the repeatability between duplicate pyknometers on each run is a further controlling measure.

In arriving at our quoted uncertainty values we have only considered those variables which affect directly the conditioning of the pyknometer and the density calculated from it. This makes the statistical approach a direct comparison to the proving of volume meters by pipe provers. To compare directly with the densitometer we must consider the repeatability achieved under field conditions between the pyknometers and the densitometers on successive runs and the reproducibility on successive visits.

Calculating overall repeatability from practical experience as detailed in Table B. From the validation exercises using 6-8 individual determinations per validation gives us an overall figure of 0.024% for crude oil.

This can further be broken down to show overall repeatability associated with installations with Twin Tube densitometers and single tube densitometers.

On Twin Tube systems 0.012%
 On Single Tube systems 0.033%

The above figures are based on the use of duplicate pyknometer results.

TABLE B

Repeatability Between Densitometer And Pyknometer Densities

PLATFORM	F I S C A L		T R A C K I N G	
	% DIFFERENCE	STD. DEV.	% DIFFERENCE	STD. DEV.
A	0.003	0.004	0.019	0.014
A	0.010	0.008	0.025	0.018
A	0.038	0.022	0.019	0.007
A	0.018	0.012	0.025	0.013
B	0.078	0.026	0.038	0.023
B	0.101	0.008	0.087	0.008
C	0.014	0.010	0.030	0.018
D	0.024	0.019	0.022	0.011
E	0.020	0.013	0.104	0.021
F	0.036	0.044	0.073	0.028
F	0.066	0.022	0.130	0.018
F	0.100	0.030	0.033	0.019
F	0.045	0.027	0.087	0.024
G	0.270	0.070	0.090	0.043
G	0.024	0.020	0.285	0.048

NGL, Condensate and Petroleum Products

This paper deals mainly with the use of pyknometry for validating crude oil systems. However we have had success in using the method to validate densitometers used in N.G.L., Condensate and Petroleum Products. This has however been restricted by the number of offshore and onshore systems where we have had practical experience.

Several problems have been encountered in the use of pyknometry on high pressure condensate analysis. The seals on the pyknometer valves is the most critical of these. To overcome this problem it has been necessary to use only new valve seats and to ensure that the valve stems are not scored in any way. This has led to a considerable improvement in the duplication achievable and the number of acceptable determinations.

The current pyknometers have a mass of about 4 kg and this ratio of mass of pyknometer to mass of fluid contained within the pyknometer means that the achievement of duplication between pyknometer is much more critical than for crude oil to obtain the same level of accuracy. Development of less dense material for pyknometer construction would result in improvements in this ratio.

To achieve acceptable levels of uncertainty for NGL and light fluids the number of determinations is often considerably higher than the 6-8 used for crudes. This may also be a factor of the densitometers and sampling systems used.

Conclusions

In the light of experience gained in the field over the last two years, Moore, Barrett and Redwood are quite convinced that pyknometry is a practical, first principles method for routine validation of fiscal systems and this method gives results compatible with the requirements of the Institute of Petroleum Part 7 section II as currently defined. The pyknometry method, with improvements in the current temperature and pressure measurement equipment, can be extended to calibrate densitometers either offline under laboratory conditions or on line in field situations.

While being recognised as a relatively expensive method of confirming densitometer calibrations consideration must be given to the independence of methodology and the high level of personnel required which gives an equally high level of confidence in the results. This must be weighed against the relative costs of the exercise.

Over and above the routine applications pyknometry can be considered as a tool with considerably wider applications in the field of oil industry measurement. Some of these are summarised here:

1. Development of confidence in density measurements performed by new online instruments and in new pipework configurations.
2. Investigations of imbalances in density measurement between Fiscal stations, providing an independent referee method.
3. Development of laboratory based calibration techniques for online and inline instruments. Under laboratory conditions the uncertainties can be reduced considerably.
4. Developments which are currently under consideration for the construction of the pyknometers from less dense materials which will improve the body weight to volume ratio. This will permit more accurate weighing and allow pyknometry to be used on light liquified products and eventually on gas systems.

NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

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**NATURAL GAS DENSITY PREDICTION IN THE HIGH PRESSURE REGION
AN EVALUATION OF DIFFERENT EQUATIONS OF STATE**

4.5

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NATURAL GAS DENSITY PREDICTION IN THE HIGH PRESSURE REGION

AN EVALUATION OF DIFFERENT EQUATIONS OF STATE.

Introduction

Offshore gas pipelines are usually characterized by high flow-rates. In the North Sea one single metering device in a fiscal metering station may measure more than 3 billion standard cubic meters per year. Natural gas is usually accounted for by mass flowrate using orifice meters. The calculation formula obtained by ISO 5167 can be simplified to:

$$Q_m = k \sqrt{2\Delta p \rho} \quad (1)$$

where Q_m = mass flow rate
 k = coefficient dependent of different factors, mainly tube and orifice diameters
 Δp = differential pressure
 ρ = density

This means that an error of 1 % in density gives an error of 0.5 % in flow rate (since density is a square root function of flow). The density error is then worth up to 2 million dollars pr. year for each metering run in one metering station.

If volumetric meters are chosen (vortex, ultrasonic, turbine meters), the density will be even more important if the gas is accounted for in mass:

$$Q_m = Q_v \rho \quad (2)$$

where Q_v = volumetric flow rate

The error in mass flow rate will now equal the error in density.

Density can today be measured by an on-line density meter within an accuracy of +/- 0.2 - 0.3 %, assuming ideal conditions. Since installation and calibration effects often will decrease this accuracy, on-line density calculation is often used to check the on-line measurement. In some countries such back-up calculation is required by the authorities.

For different reasons (e.g. cost, stable gas composition, or bad experience with density meters), some like to exclude density measurement in preference to on-line density (or compressibility) calculation - usually combined with an on-line gas chromatograph or sampler.

The density may be calculated by using the non-ideal gas law:

$$\rho = \frac{P \text{ MW}}{z R T} \quad (3)$$

where
 P = pressure
 MW = mole weight
 R = universal gas constant
 T = temperature
 z = compressibility factor

Pressure and temperature are usually measured anyway, and mole-weight is known from composition. The compressibility factor (or z-factor) is then found from an equation of state (z-factor equation). Apart from different fixed parameters for each gas component; temperature pressure and composition (x) are usually the only necessary inputs:

$$z = f(T, P, x) \quad (4)$$

The supercompressibility factor (Fpv) - often used in the U.S. in the AGA 3 method - is related to the z-factor by:

$$F_{pv} = \sqrt{\frac{z_b}{z}} \quad (5)$$

where
 Fpv = supercompressibility factor
 z_b = compressibility at base or standard condition (14.73 psia, 60 F)

Apart from being a fundamental parameter in natural gas metering, the compressibility factor is also a key parameter for calculating other thermodynamic properties for natural gas mixtures like enthalphy, entropy, isentropic exponent, velocity of sound, viscosity, etc. Research on state equations should for that reason have interest to a broad range of engineers for process and metering calculations.

Experimental data.

An investigation into the accuracy of equations of state requires first of all - experimental data for comparisons.

Statoil and Rogaland Research Institute (Norway) organized last year a joint project to establish a database - DENSBASE (14). The database was later updated (15) within Statoil and contains now more than 2000 experimental compressibility and density data distributed among 83 different compositions of natural gases and similar laboratory made gases. The database have the necessary possibilities for graphics and search commands.

Why collect all these experimental data when comparisons with state equations have been done before? Several articles about such comparisons have been published, and the paper presented by GERG Information Committee (1) is probably the most extensive and well known.

However, this and other papers concentrate their work in the pressure range up to 100 bara (1450 psia). In North Sea pipelines - the pressure is often above 100 bara and it may even exceed 200 bara (2900 psia). Experimental data and comparisons between

experimental and calculated results are very limited within this pressure range.

Equations of state.

Six different equations of state were compared with experimental data:

- VENNIX-KOBAYASHI (2); a method originally developed for methane, but later adjusted to lean natural gas mixtures.
- OU/GRI (AGA Report No 8) (3); A recently developed method which cover a wide range of natural gas components. This method has now replaced the NX 19 method (4). Comparisons between OU/GRI and NX 19 has been done earlier by Starling & Kumar (3,5). NX 19 was for that reason only tested with a few points in the work presented in this paper.
- STANDING & KATZ (6) is a simple method widely used in flow-computers.
- BENEDICT-WEBB-RUBIN (BWR) (7,8) and
- SOAVE-REDLICH-KWONG (SRK) (9) are well known state equations widely used in the process as well as the metering industry. One should be aware that there are several versions of these equations.
- PENELOUX (10) is a modification of the SRK method.

(The Peng-Robinson(11) method was also compared with a few points versus the Peneloux method but did not give promising results.)

Coefficients or other parameters have not been adjusted to improve the results. The aim of the evaluation was to investigate the accuracy of different available methods. The program SONFLOW (16) has computed the z-factors for Vennix- Kobayashi, BWR and OU/GRI; Katz (17) is the computerprogram for the Standing-Katz method and Statpack (18) is used for SRK and Peneloux.

Results and discussions.

The first problem one meets when comparing experimental and calculated values is: Which is right? In other words; Are the accuracies of the experimental data satisfactory and within the claims of the experimentalists?

The ideal situation would be to let two laboratories measure the same gas with different equipment, and then compare the results. This is often done for pure components, where comparisons are easy. For natural gas mixtures, this would require close cooperation between laboratories since exchange of gas samples would be necessary. Unfortunately, this is not often the case, especially not in the pressure area above 100 bara (1450 psia).

It was decided to make a first comparison between the experimental data and an equation of state experienced to give a good accuracy in the pressure area below 100 bara. The OU/GRI method was selected

because the accuracy of this equation is well documented in the literature (5).

For the uncertainty analysis the average absolute percent deviation was used:

$$\text{A.A.D. (\%)} = \frac{1}{n} \sum_{i=1}^n \left| \frac{\text{exp}_i - Z_{\text{calc}_i}}{Z_{\text{exp}_i}} \right| \cdot 100 \quad (6)$$

We carefully picked datapoints mainly in the range from 100 to 250 bara (1450-3625 psia) with a few controlpoints below 100 bara. Since the deviation is larger in the high pressure area than in the low pressure area, one should be aware that to include a lot of good low-pressure data would give a "better" - but more misleading - overall accuracy.

The temperature range was from 0 to 100 C (32 - 212 F). The results are given in Table 1 and the conditions are given in Table 2.

Total Oil Marine (U.K), Elf Aquitaine (Norway), The Norwegian Petroleum Directorate and Statoil (Norway) are now running a joint research project with the Dantest Laboratory (Denmark) to investigate natural gas density meters. After 3 years of different comparisons between density meters and experimental densities obtained by a laboratory z-meter, we are now confident that the results are within 0.1% accuracy. The Dantest results (12,13) are for that reason shown separate. The last serie of experiments with comparisons are given in Fig. 1 and Table 3, since these results give a representative view of the overall comparison.

Conclusions.

- 1) The comparisons of 6 equations of state versus experimental data gave the following ranking (average absolute deviation is given in parenthesis):
 - * OU/GRI and Vennix-Kobayashi (0.3 %)
 - * Benedict-Webb-Rubin (0.4 %)
 - * Standing & Katz (1.1 %)
 - * Peneloux (2.2 %)
 - * Soave-Redlich-Kwong (2.8 %)
- 2) Both OU/GRI and V-K gave an average absolute deviation of 0.3 %. However, at pressures of about 200 bara there is no reason to expect better accuracy than 0.5 %.
- 3) V-K seems to be the best available method for lean gases (C1 > 85 mole %) up to 150 bara, but are not suitable for gases with a high C3 + - fraction.
- 4) The simple Standing & Katz method which is widely used in flowcomputers, seems to be capable of calculating z-factors/densities to an accuracy of 1.5 % in the total PVT-range of interest to practical gas metering. Compared with most references the Katz densities are too high (Katz z-factors too

low). This is also experienced by comparisons against density meters at the Kårstø terminal.

- 5) SRK and Peneloux are not suitable methods for calculating high pressure z-factors/ densities of interest for gas metering purposes (note that other modifications of the Redlich-Kwong than SRK may give other results).
- 6) There is an obvious need for accurate measurement of z-factors in the pressure range 100 to 200 bara (1450 - 3625 psia).
- 7) The experimental data for gases close to the dew point are uncertain. At low temperatures there is a big scatter between experimental z-factors and also between the different state equations.

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18. "STATPACK - manual for the program package", User Manual from CALSEP, Okt. 1986.

	BWR	V-K	OU/GRI	S-Katz	SRK	Peneloux
Dantest	0.18	0.09	0.12	0.97	1.49	1.15
All points	0.38	0.30	0.29	1.09	2.79	2.18

Table A1: Average absolute percent deviation between experimental and calculated z-factors.

	MW	Methane	P-bara (psia)	T C (F)
Dantest	17.1-18.8	93.8-82.7	10-150(145-2175)	30-35 (86-95)
All points	16.0-18.8	100 -82.7	10-300(145-4351)	0-67 (32-152)

Table A2: Range for mole weight, methane content (mole percent), pressure and temperature for the test points.

REF 83 P (BARA)	T = 30 C EXP. Z	BWR	DEV	V-K	DEV	GRI/OU	DEV
10.0220	.9775	.9766	.0920	.9766	.0920	.9769	.0613
20.0320	.9543	.9532	.1152	.9534	.0943	.9538	.0523
30.0410	.9315	.9304	.1180	.9299	.1717	.9309	.0644
40.0500	.9088	.9069	.2090	.9077	.1210	.9082	.0660
50.0600	.8867	.8843	.2706	.8855	.1353	.8860	.0789
70.0800	.8445	.8415	.3552	.8434	.1302	.8435	.1184
90.0900	.8067	.8038	.3594	.8061	.0743	.8057	.1239
110.1100	.7768	.7740	.3604	.7762	.0772	.7752	.2059
130.1200	.7560	.7542	.2380	.7557	.0396	.7544	.2116
150.1400	.7457	.7449	.1072	.7458	.0134	.7440	.2279
BIAS (%)			.2225			.0922	.1211
AVER. ABS DEV (%)			.2225			.0949	.1211

REF 83 P (BARA)	T = 30 C EXP. Z	ST-KATZ	DEV	SRK	DEV	PENELOUX	DEV
10.0220	.9775	.9757	.1841	.9771	.0409	.9767	.0818
20.0320	.9543	.9513	.3143	.9545	.0209	.9537	.0628
30.0410	.9315	.9271	.4723	.9323	.0858	.9311	.0429
40.0500	.9088	.9032	.6161	.9108	.2200	.9092	.0440
50.0600	.8867	.8797	.7894	.8900	.3721	.8880	.1466
70.0800	.8445	.8350	1.1249	.8517	.8525	.8490	.5328
90.0900	.8067	.7959	1.3387	.8196	1.5991	.8161	1.1652
110.1100	.7768	.7654	1.4675	.7958	2.4459	.7914	1.8795
130.1200	.7560	.7457	1.3624	.7815	3.3730	.7763	2.6851
150.1400	.7457	.7372	1.1398	.7766	4.1437	.7706	3.3391
BIAS (%)			.8810			1.3072	.9604
AVER. ABS DEV (%)			.8810			1.3154	.9980

Table A3: Comparisons between experimental z-factors from the Dantest project (12,13) and calculated z-factors from different state equations. (The experimental values are not previously released. The exact temperature vary from 29.95 to 29.99 C)

Composition (mole %): N2: 0.62 C3: 1.04
CO2: 0.79 iC4: 0.04
C1: 82.71 nC4: 0.08
C2: 14.70 C5: 0.00
C6: 0.01

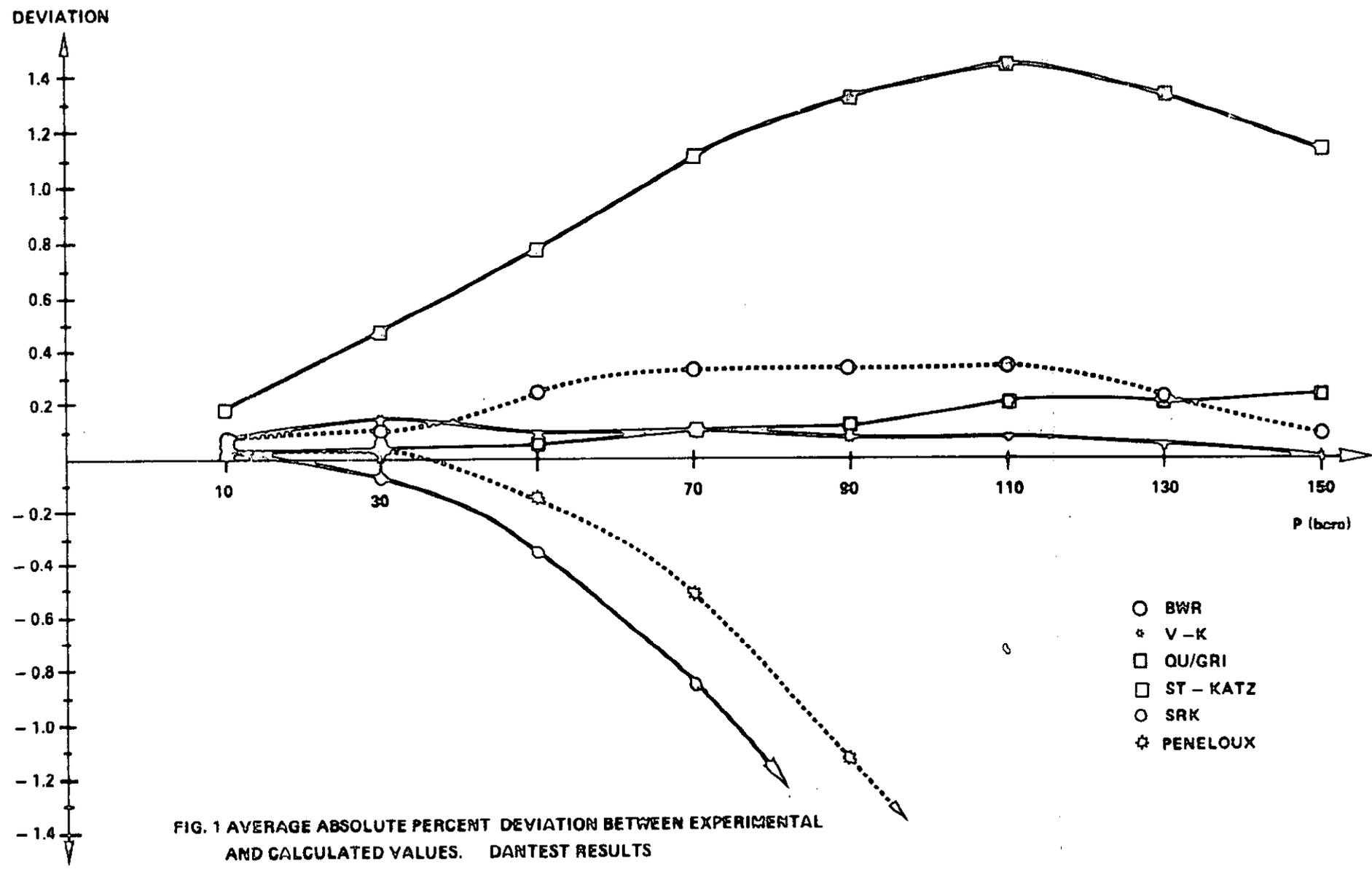


FIG. 1 AVERAGE ABSOLUTE PERCENT DEVIATION BETWEEN EXPERIMENTAL AND CALCULATED VALUES. DANTEST RESULTS

5.1

**WORLDWIDE EXPERIENCE WITH
SMALL VOLUME PROVERS**

By

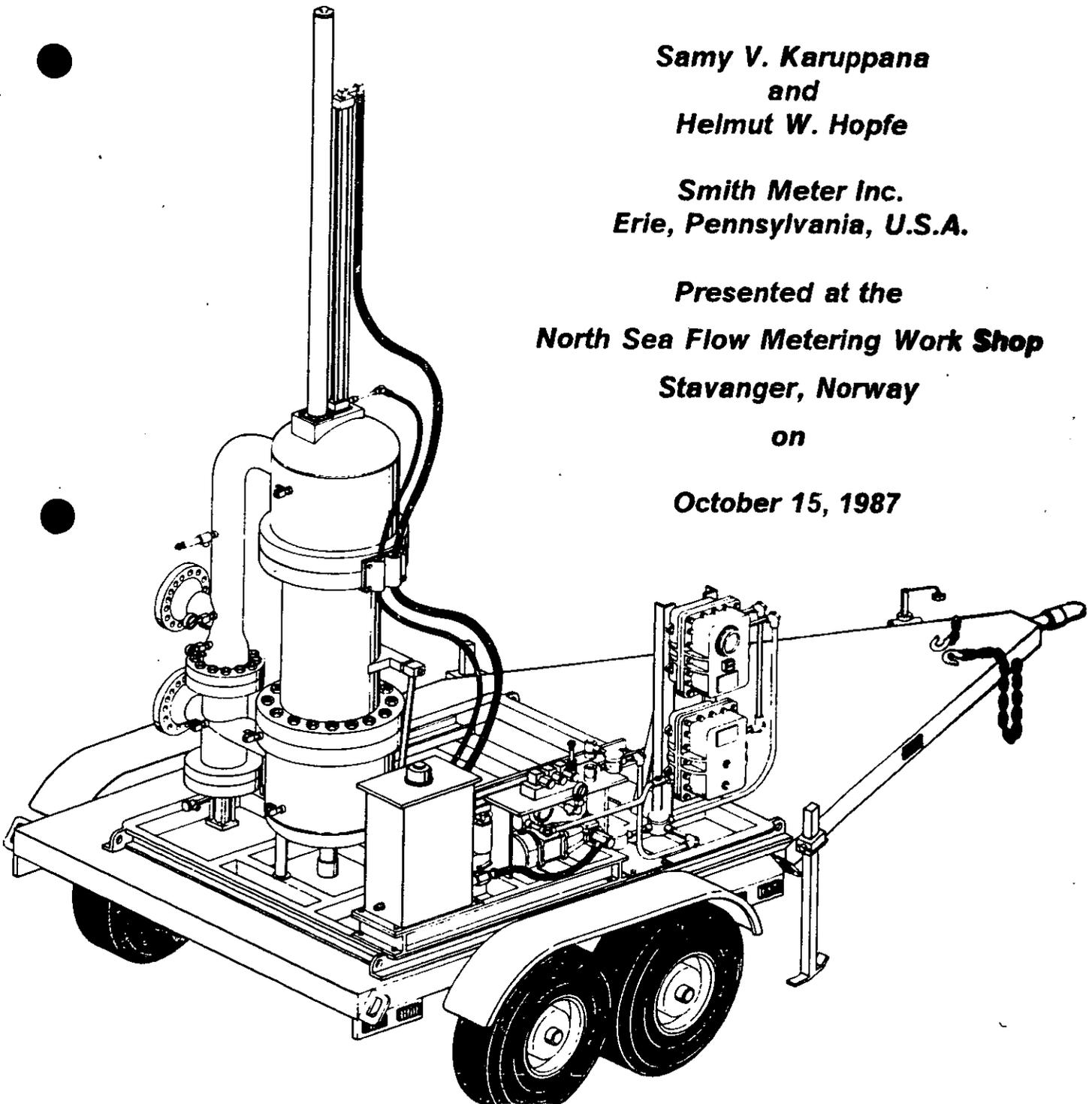
**Samy V. Karuppana
and
Helmut W. Hopfe**

**Smith Meter Inc.
Erie, Pennsylvania, U.S.A.**

**Presented at the
North Sea Flow Metering Work Shop
Stavanger, Norway**

on

October 15, 1987



SUMMARY

This paper discusses some of Smith Meter's worldwide experience with small volume provers. Accuracy, repeatability, reliability, cost, safety requirements and approvals, and weights and measures approvals are subjects of discussion in this paper.

INTRODUCTION

At present, throughout the world, small volume provers are being accepted as one of the standard pieces of equipment for calibrating liquid flow meters. The universal acceptance of small volume provers is relatively new and the industry is continuing to learn more about their application.

ACCURACY

Waterdraw Test Measures

The absolute accuracy of the volume of an SVP is only as good as the test measure used to calibrate the SVP. Table 1 shows the typical uncertainty of waterdraw test measures used in practice today. Figure 1 shows a 15 gallon test measure typically used in the U.S.A., designed and manufactured by Seraphin Test Measure Company and calibrated by the National Bureau of Standards. Figure 2 shows a 57 liter (42 gallons) test measure typically used in the Federal Republic of Germany, designed and manufactured by Smith Meter GmbH and calibrated to PTB (Physikalisch-Technische Bundesanstalt) standards by local weights and measures authorities. There are many reasons for the uncertainty in the U.S.A.'s measure being ten times higher than the test measure used in the Federal Republic of Germany, and it is beyond the scope of this paper to discuss those reasons in detail. Manufacturers, regulatory agencies, and users throughout the world are working together to design, calibrate, and use test measures with the least uncertainty to get the best possible measurement accuracy.

COUNTRY OF ORIGIN	VOLUME DELIVERED	ESTIMATED UNCERTAINTY
U.S.A.	14.9959 Gallons at 60°F.	+/- 1.08 cu.in. (+/- .031%)
U.S.A.	41.9924 Gallons at 60°F.	+/- 3.6 cu.in. (+/- .037%)
FED. REP. OF GERMANY	57 L (15 Gallons) at 20°C.	+/- 2 ml (+/- .004%)
FED. REP. OF GERMANY	159 L (42 Gallons) at 20°C.	+/- 5 ml (+/- .003%)

Table 1: Typical Uncertainty of Waterdraw Test Measures



Figure 1

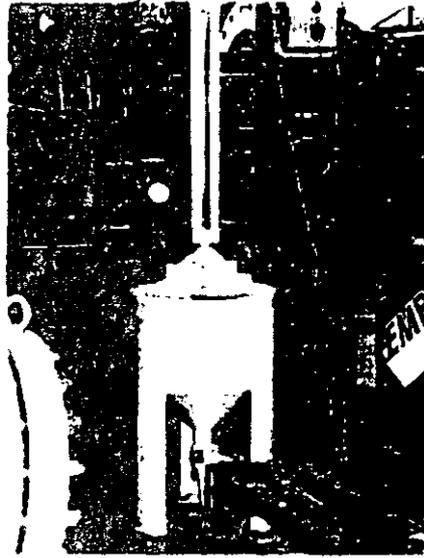


Figure 2

Temperature Effect During Waterdraw Calibration

It is commonly known that a reliable calibration of any prover, conventional ball prover or small volume prover, requires stabilized temperature conditions. Therefore, the water is circulated multiple times through the prover before calibration, during which time the ambient and water temperatures must remain constant. The purpose of this procedure is to minimize the temperature difference between the prover's hardware (pipe) and the water if the ambient temperature deviates from the temperature of the test liquid used for calibration (see Figure 3).

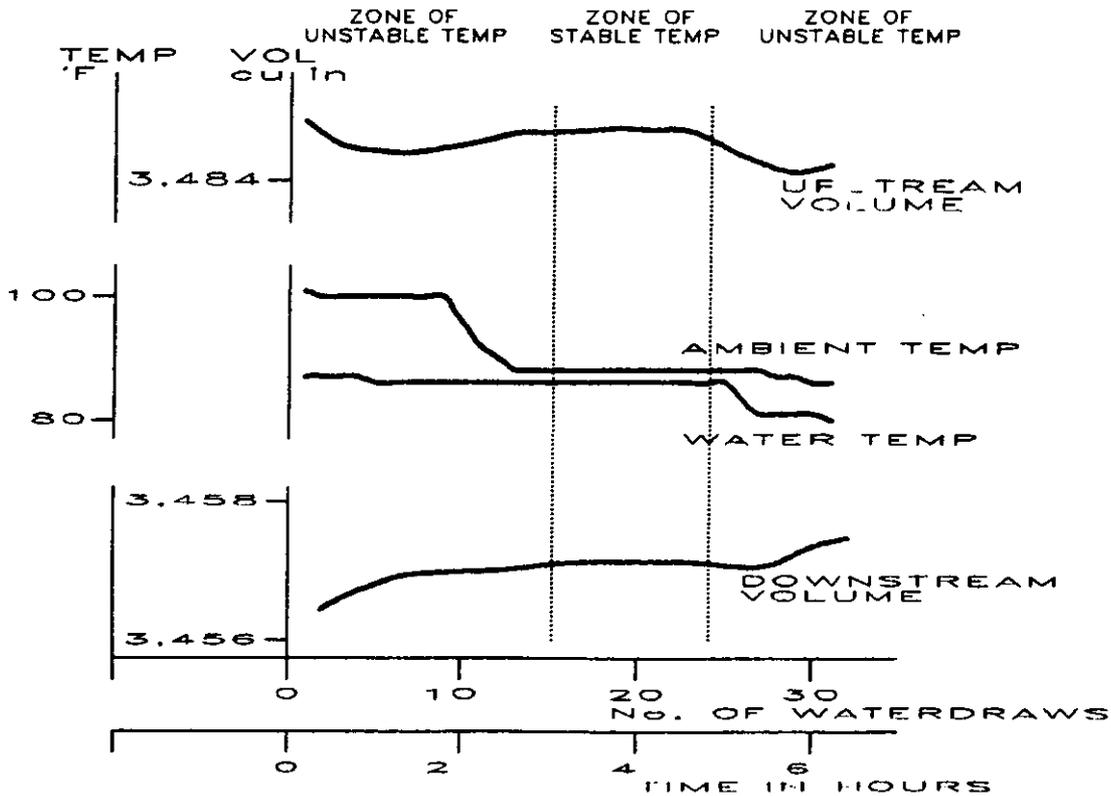


Figure 3

The calibration of an SVP is more significantly affected by temperature difference, that is ambient temperature versus water temperature, in comparison with conventional provers. The reasons for this are the natures of the SVP's design and operation. The more stringent temperature requirements for SVP calibration can be explained as follows:

1. Detector Rod Expansion or Contraction

Most SVP's feature a detector rod connected with the displacer and extended through a journal bearing externally to the prover vessel. This kind of arrangement exposes the detector rod partially to ambient and partially to water, the liquid generally used for calibration. The degree of exposure to either medium is a function of the displacer's position. At waterdraw velocity, approximately .001 to .01 ft./sec., the rod's exposure changes constantly. If the ambient temperature differs from the water temperature, the rod is either contracting or expanding during the calibration process. This causes the rod's target flag (used to actuate the detector switches) to travel faster or slower than the prover's displacer, resulting in faulty calibration. Therefore, the ideal temperature condition during calibration is established when the ambient temperature is equal to the water temperature. A temperature difference up to 5°F may be acceptable based on test data and the following example.

Example of calibration error:

Stroke of Detector Rod:	27.25"
Dia. of Measurement Section:	12.75"
Volume:	15 Gallons
Water Temperature:	T°F
Ambient Temperature:	T° +/-5°F

$$\begin{aligned} \Delta L_{\text{Det. Rod}} &= L \times \Delta T \times \text{linear coefficient of thermal expansion of rod} \\ \Delta L_{\text{Det. Rod}} &= 27.25 \text{ inch} \times 5^\circ\text{F} \times .0000063 \text{ inch/inch}^\circ\text{F} \\ \Delta L_{\text{Det. Rod}} &= .00086 \text{ inch} \end{aligned}$$

The rod's expansion or contraction of .00086 inch is equivalent to a calibration uncertainty of +/-0.11 cu.in., or +/-0.0032%. The results may vary, depending on the prover's nominal volume and the actual distance between the detector switches.

2. Expansion or Contraction of Prover's Piping

In general, SVP's require more metal per unit of calibration volume compared to conventional provers, necessitating a longer time for temperature stabilization. The total calibration error due to non-stabilized temperature conditions is a superimposition of the following:

- Volume error due to expansion or contraction of the SVP's piping
- Volume error due to expansion or contraction of the detector rod.

Calibration values achieved at different temperature conditions (Figure 3) indicate that the magnitude of error due to unstable piping temperature is much greater than the computable error due to length changes of the detector rod. Recommended practice is to bring the water temperature to be within +/-5°F of the ambient temperature.

Temperature Effect During Meter Proving

What is the impact on meter factor accuracy due to expansion and contraction of detector rod and piping when product temperature is different from ambient temperature? The theoretical analysis and experiments indicate that no noticeable error due to this expansion or contraction phenomenon exists when proving at normal flow range. For example, let us study the data in Table 2. The ambient temperature during these tests was 75°F. Hence, the temperature difference between ambient and product varied from 11.7°F to 29.6°F. But, in all these conditions, the meter factors derived from the SVP agree with meter factors derived from the conventional prover. At these flow rates, the proving time is short and, hence, there is not sufficient time to expand or contract.

The effect of this phenomenon at very low flow rates is under study now. A well insulated prover and other means, which keep the detector rod very close to the product temperature, will eliminate this concern. The results of this study will be published in a future technical paper.

Effect of Using Flexible Hoses

The application of hoses to facilitate the connection of an SVP to a flow meter run may result in unreliable meter factors and decreased repeatability values. The magnitude of the meter factor errors is influenced by the following:

- pressure rating of hose
- length of hose
- line pressure
- hose arrangement

To determine the impact of this error, actual tests were performed using an SVP with the following arrangements:

- A. SVP interconnected with hoses
- B. SVP interconnected with hard piping.

In addition, a conventional ball prover was installed in series with the SVP and the flow meter to establish meter factors under identical conditions.

Test Conditions:

Test Arrangement:	See Figure 5
SVP Type:	15 Gallon Volume, 12.75" Bore
Conventional Prover Type:	Unidirectional Ball Prover, Volume 2,269.5 Gallons
Meter Type:	6" P.D. Meter, Non-Cyclic
Test Liquid:	Kerosene
Product Pressure:	35 PSIG @ 600 GPM, 50 PSIG @ 1200 GPM
Product Temperature:	39 to 42°F
Flow Rates:	600 GPM and 1200 GPM
Type of Hose:	6" Fuel Discharge Hose, 6" I.D., 6.781" O.D., 16' Long Applied Upstream & Downstream to SVP, 150 PSI Max. W.P.

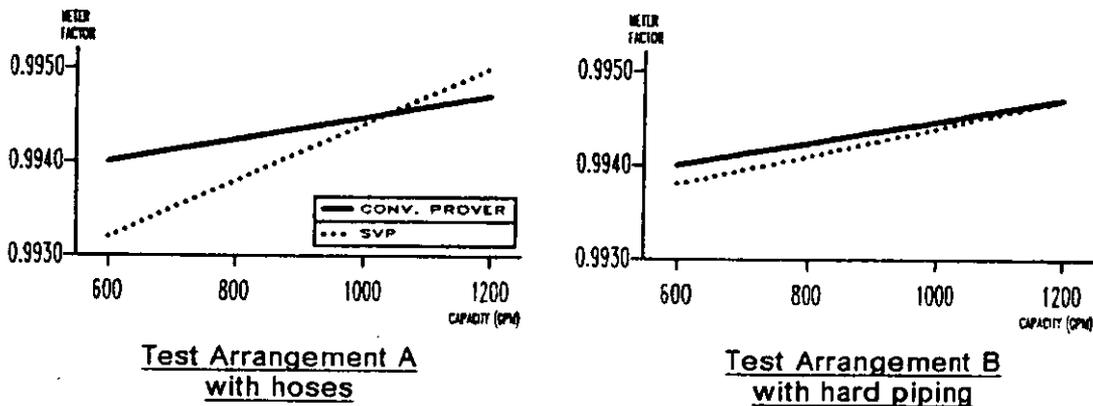


Figure 4

As Figure 4 indicates, when hard piping is used, the meter factors derived using an SVP and a unidirectional prover were almost identical. Whereas, when hoses are used, the meter factor derived using an SVP is off as much as 0.1%. Hence, the need to use hard piping is more critical in an SVP application than that of a large conventional prover.

REPEATABILITY

A typical SVP is a very repeatable piece of equipment. It is common practice to expect, when proving a meter, a system repeatability of .05% or better for five consecutive runs.

Many of the commonly used meters, positive displacement meters with various accessories and even some turbine meters, may not meet these requirements. Decreasing the cyclic output of the meter has been the focus of attention. For turbine meters, controlling the manufacturing tolerance produced meters with acceptable non-cyclic output. The situation is much more complex for P.D. meters. A combination of (1) redesign, e.g., eliminate "Hooks" type coupling, (2) tight manufacturing tolerances, e.g., more uniform gears, (3) changes in operating procedure, e.g., application of electronic meter factor correction, (4) changes in proving procedure, e.g., group proving, may provide satisfactory performance.

Figure 5 shows a test setup used to study the repeatability and meter factor accuracy of an SVP proving versus conventional proving. Table 2 summarizes the results of a turbine meter test. Table 3 summarizes the results of a P.D. meter test. The following conclusions can be derived from Tables 2 and 3.

- Repeatability of .05% or better can be achieved by 5 consecutive proving runs.
- Meter factor agreement of .05% or better can be achieved between SVP proving and conventional proving using 5 consecutive runs.
- Two groups of ten consecutive runs produces much improved correlation between meter factors.

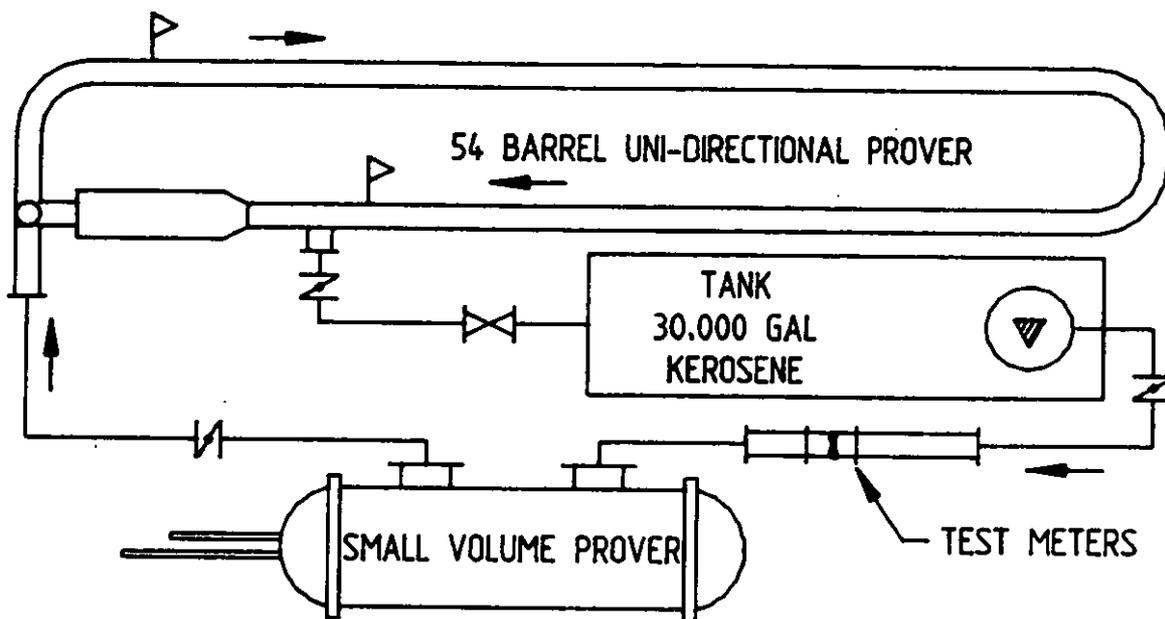


Figure 5: SVP vs. Unidirectional Prover Test Arrangement

FLOW RATE (BPH)	PROVER TYPE	TEMP. DEG.F	SVP - 2 GROUPS OF 10 CONS. RUNS UNI - 3 CONSECUTIVE RUNS			SVP - 5 CONSECUTIVE RUNS UNI - 3 CONSECUTIVE RUNS		
			REPEAT. (%)	METER FACTOR	DEVIATION (%)	REPEAT. (%) 5 CONS. RUNS	METER FACTOR	DEVIATION (%)
TEST #1								
1,484	SVP	86.7	.0073	1.0075	0	.0090	1.00768	
	Unidirect. Prover	87	.0132	1.0075		.0132	1.00750	.018
TEST #2								
7,103	Unidirect. Prover	101	.0132	1.0060	0	.0132	1.00600	
	SVP	102.8	.0000	1.0060		.0400	1.00593	.007
TEST #3								
7,103	Unidirect. Prover	103.5	.0099	1.0060	0	.0099	1.00600	
	SVP	104.6	.0067	1.0060		.0479	1.00608	.008

54 Barrel Unidirectional Prover, 42 Gal. SVP, 10" Smith Sentry Series Turbine Meter Test Setup per Figure 5.

Table 2: SVP3 Repeatability & Accuracy Test

FLOW RATE (BPH)	PROVER TYPE	TEMP. DEG.F	SVP - 10 CONSECUTIVE RUNS UNI - 3 CONSECUTIVE RUNS			SVP - 5 CONSECUTIVE RUNS UNI - 3 CONSECUTIVE RUNS		
			REPEAT. (%)	METER FACTOR	DEVIATION (%)	REPEAT. (%) 5 CONS. RUNS	METER FACTOR	DEVIATION (%)
TEST #1								
867	SVP	37.5	.0245	.9957	.02	.0079	.99564	
	Unidirect. Prover	39.5	.0303	.9955		.0303	.99550	.014
TEST #2								
1,656	SVP	42	.0192	.9984	.01	.0133	.99837	
	Unidirect. Prover	42.5	.0220	.9983		.0220	.99830	.007

54 Barrel Unidirectional Prover, 15 Gal. SVP, 6" Smith Non-Cyclic P.D. Meter Test Setup per Figure 5.

Table 3: SVP1 Repeatability & Accuracy Test

RELIABILITY

This subject can be subdivided into two categories. The first category is the reliability of the mechanical, hydraulic, and electronic hardware, and the computer software. The second category is the reliability of the calibration data derived from the use of the SVP. Like many new products, the SVP experienced some reliability problems during its initial stage. Now, most of these problems have been recognized, understood, and corrected. The longevity of the main displacer seal has been significantly improved by using improved seal material, refining the details of mechanical design, and operating the prover in a vertical position when the product is not clean.

The new generation of SVP's has the means to monitor all seals, including the main displacer seals, and bypass valve seals during each proving cycle, which helps to improve the reliability of data obtained from SVP proving. There are hundreds of small volume provers in all parts of the world. With few exceptions, all these provers are functioning reliably.

COST

Cost is a very important factor in buying and using a particular piece of equipment to perform a useful service. Figure 6 shows a cost comparison between small volume provers and conventional bidirectional provers. The graphical presentation shows that the initial cost of a small volume prover is slightly higher than the conventional bidirectional prover. The size, weight, ability to prove at very low flow rates, and compatibility to a wide range of products are some of the reasons that small volume provers are preferred.

Small volume provers have more parts and complex mechanisms than conventional provers. Hence, the maintenance cost of a typical small volume prover may be higher than a conventional prover.

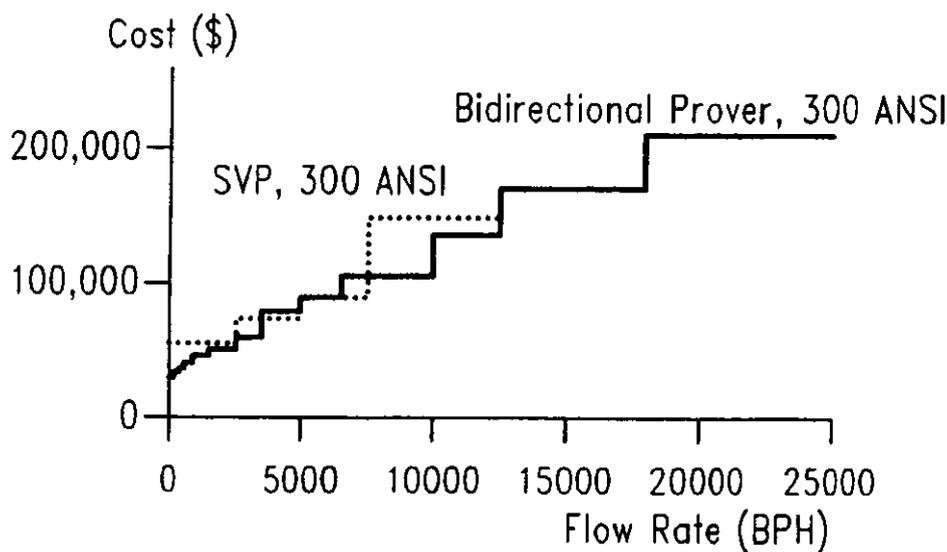


Figure 6: Small Volume Prover Cost

SAFETY REQUIREMENTS AND APPROVALS

This subject can be subdivided into two categories. The first category is the safe use of an SVP as a pressure vessel. The second category is the electrical safety, that is, the safe use of an SVP in hazardous locations. What are the requirements? What are the design codes, manufacturing procedures, and Quality Assurance standards to be met? What are the regulatory approvals required?

Tables 4, 5, and 6 show some typical examples of current practices related to SVP safety requirements and approvals. Currently, SVP's are being accepted based on meeting appropriate pressure vessel codes and the use of electrical components which are approved individually. So far, there is no market demand necessitating an electrical safety approval of the SVP as a system. The acceptance of design codes for pressure containing parts and the type of approval required for electrical components varies from country to country.

GEOGRAPHICAL AREA	TYPE OF CODE	REMARKS
<i>North America</i>	<i>Standard: ANSI B31.4. Option: ANSI B31.3 and others.</i>	<i>Accepted in U.S.A., Canada, Australia, and South America.</i>
<i>Federal Republic of Germany</i>	<i>Standard: According to Specifications of "AD-MERKBLAETTER", to TUEV standards. Option: - TRBF. - ASME Certified by TUEV. - Other European Pressure Vessel Codes.</i>	<i>Generally Accepted throughout the European Community.</i>

Table 4: SVP Pressure Vessel Requirements, Codes, and Approvals

GEOGRAPHICAL AREA	TYPE OF APPROVAL	REMARKS
<i>North America</i>	<i>Standard: UL, FM, or CSA.</i>	
<i>Federal Republic of Germany</i>	<i>Standard: UL. Option: CENELEC (including flexible cable inter-connection of electrical components).</i>	

Table 5: SVP Electrical Safety Approvals

GEOGRAPHICAL AREA	TYPE OF APPROVAL	REMARKS
<i>North America</i>	<i>Exemption Notice #DOT-E9728 U.S. Government Department of Transportation Office of Hazardous Materials Transportation.</i>	<i>This issue is under review by DOT.</i>

Table 6: United States Department of Transportation Requirements for SVP

WEIGHTS AND MEASURES APPROVALS

The SVP is a calibration device used to calibrate meters and large provers which are used in commerce as standards of measurement. Hence, almost all SVP's are subject to the approval of the weights and measures authorities. Generally, weights and measures are controlled by government agencies. Each country has its own agency and, hence, manufacturers and users must obtain weights and measures approval from each country where the prover will be used. Generally, there has been no problem in obtaining weights and measures approval. Table 7 shows some typical examples of current practices related to SVP weights and measures approvals.

GEOGRAPHICAL AREA	TYPE APPROVAL	REMARKS
<i>North America</i>	<i>No type approval required. The SVP's calibration is considered to be verified through its traceability to test measures certified by NBS (National Bureau of Standards) and CCA (Consumer and Corporate Affairs, Canada).</i>	<i>Accepted in Canada, Australia, and South America.</i>
<i>Federal Republic of Germany</i>	<i>PTB - Certificate Issued. Waterdraw traceable to Federal Republic of Germany national standards.</i>	
<i>Netherlands</i>	<i>Weights and Measures Acceptance Test complete. - Certificate to be issued.</i>	
<i>Norway</i>	<i>Weights and Measures Acceptance Test complete. - Certificate to be issued.</i>	
<i>United Kingdom</i>	<i>Weights and Measures Certificate issued.</i>	

Table 7: SVP Weights and Measures Approvals

CONCLUSION

In this paper, the authors shared with you some of Smith Meter Inc.'s worldwide experience in designing, manufacturing, and operating small volume provers. Our experience indicates that the SVP is a very useful device and further enhancements, which are now underway, will make it even better.

User experience with Smith SVP

Author: Tore Revå, Esso Norge a.s

5-2

1. System configuration

The Slagen turbine meter system consists of four 8" turbine meters for loading of light products, and a Smith Small Volume prover for calibration of these meters. Each turbine meter can handle different products with very similar physical properties. (Viscosity, density.....). Product and Loading arm selection is performed by remotely operated double block and bleed valves. Temperature and pressure is measured after each turbine meter, and inside the prover. (See attached P&ID).

A quick look at the plot plan gives a fairly good impression of the large amount of straight pipe before each turbine 100 D, giving extremely stable flow conditions.

The system block diagram indicates that two different systems are involved in the proving system. TDC-2000 is used for valve selection, pump start and flow control, while the Smith Geoprov is controlling the prover itself and recording temperatures and pressures from the prover and the meter being calibrated.

2. Project History

The turbine meter system including SVP was ordered in December -84 for delivery in August -85. The system was constructed in USA with CSA approval, and had to be converted to Cenelec standard in Germany. Due to limited access of large lifting facilities on Slagen pier, the system was accepted for shipment to Slagen before the equipment was converted to Cenelec standard.

Despite excellent work from Smith in Germany the field retrofit was not finished before April -86.

A number of small leaks and system outages in the following year led to the decision in April 87 to send the prover back to Smith in Germany for adaption to Smith's latest design. After this retrofit the prover seems to be operating much more stable, without any serious out of service period.

3. System performance

The system performance must be split into two completely different areas, the accuracy of the system and the availability of the system.

Accuracy has never been a severe concern in the system, because it has proved to be repeatable and stable as long as no actual error occurs. The attached calibration charts indicate the meter and prover performance for successful calibration runs.

Availability has on the contrary, been a more or less constant problem for the system, until the last factory repair and testing, which seems to have resolved the previous problems. The low availability is basically caused by three factors:

- Unstable prover - many small problems.
- Long repair time in the beginning - lack of experience.
- Long waiting time due to ship availability.

4. User experience, SVP

4.1 Operational experience.

Prover operation is convenient through the Geoprov computer, which controls complete series of 25 strokes with the prover, recording meter pulses, flowrate, temperature and pressure automatically. Compensation is performed automatically by the Geoprov, and the results presented in a printed report. A tracking of each meter from proving series to proving series must be performed outside the system, but the printed reports gives an excellent tool to implement this tracking.

Experience has shown that it is not easy to keep track of all the different parameters in the system, and dedicated, qualified personal must be involved in the proving, despite the highly automated procedures.

4.2 Problems revealed.

The prover was suffering from a number of small deficiencies occurring during proving, especially leaks and problems with detector switches. The hydraulic shocks experienced during each proving cycle was also causing severe vibration in the prover.

Major areas of leakage were the following:

- The pressure balance valve.
- Sealing between instrument rod and main cylinder.
- Shock absorbers.
- Main seal of prover (breakdown once).

The optical detector switches were in one occasion misaligned to the degree that the flags operating the switches crashed completely. This occurred "spontaneously", i.e. the prover was not operated between successful waterdraw calibration and the fatal run.

This incident caused the vendor to accept a factory retrofit of the prover to comply with Smiths latest prover design. So far, this retrofit seems to be a success.

5. User experience - system design.

Our system design is convenient when the system is working perfectly, but the lack of a return system is causing problems during maintenance work. It is a timeconsuming process to wait for a ship to arrive and then start faultfinding, as compared to the process of repairing and testing all systems before the ship arrives.

The SVP at Slagen is installed in the vertical position. This is excellent from a lifetime point of view because excess wear and dirt collection is avoided, but maintenance of the instrument rod is much more complicated than in the horisontal position.

The installation on the pier itself causes some additional problems, primarily severe weather conditions and hazardous area operation. Normal operation of the prover and turbine meter systems is convenient and simple due to remote control through TDC-2000 and Smith Geoprobe computer. Different people are operating the control system and the Geoprobe itself. They are communicating through a telephone line, and this seems to be working perfectly. However, The Geoprobe could be placed in the control centre to simplify this communication further, subject to space limitations. Different people would still be needed to operate the Geoprobe and the TDC-2000, because proving must be performed by another department than the operations department.

6. Lessons to be learned.

6.1 Project followup.

The Slagen SVP was a pilot project for Smith in Europe, and more tight followup during engineering and construction in the US and Europe could have avoided some of the startup problems.

Despite the extra expences caused by a delayed installation, the prover should not have been accepted at factory commissioning before all conversions to Cenelec standard were performed and the system was proved 100% operational.

6.2 System design.

The need of an adequate return system or another test possibility cannot be overemphasized.

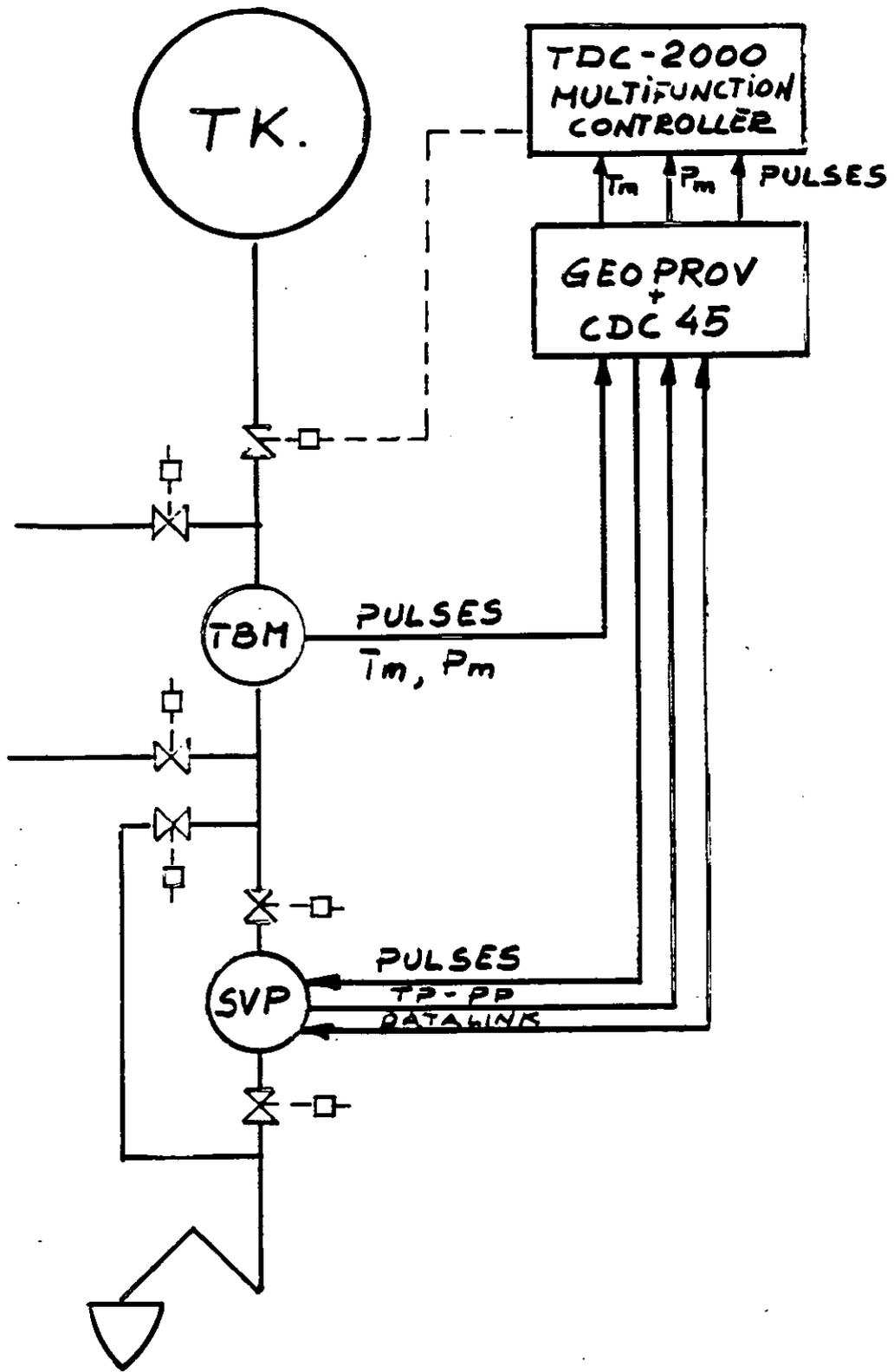
In order to simplify maintenance work, and also weather protection of the prover, horisontal installation should be considered.

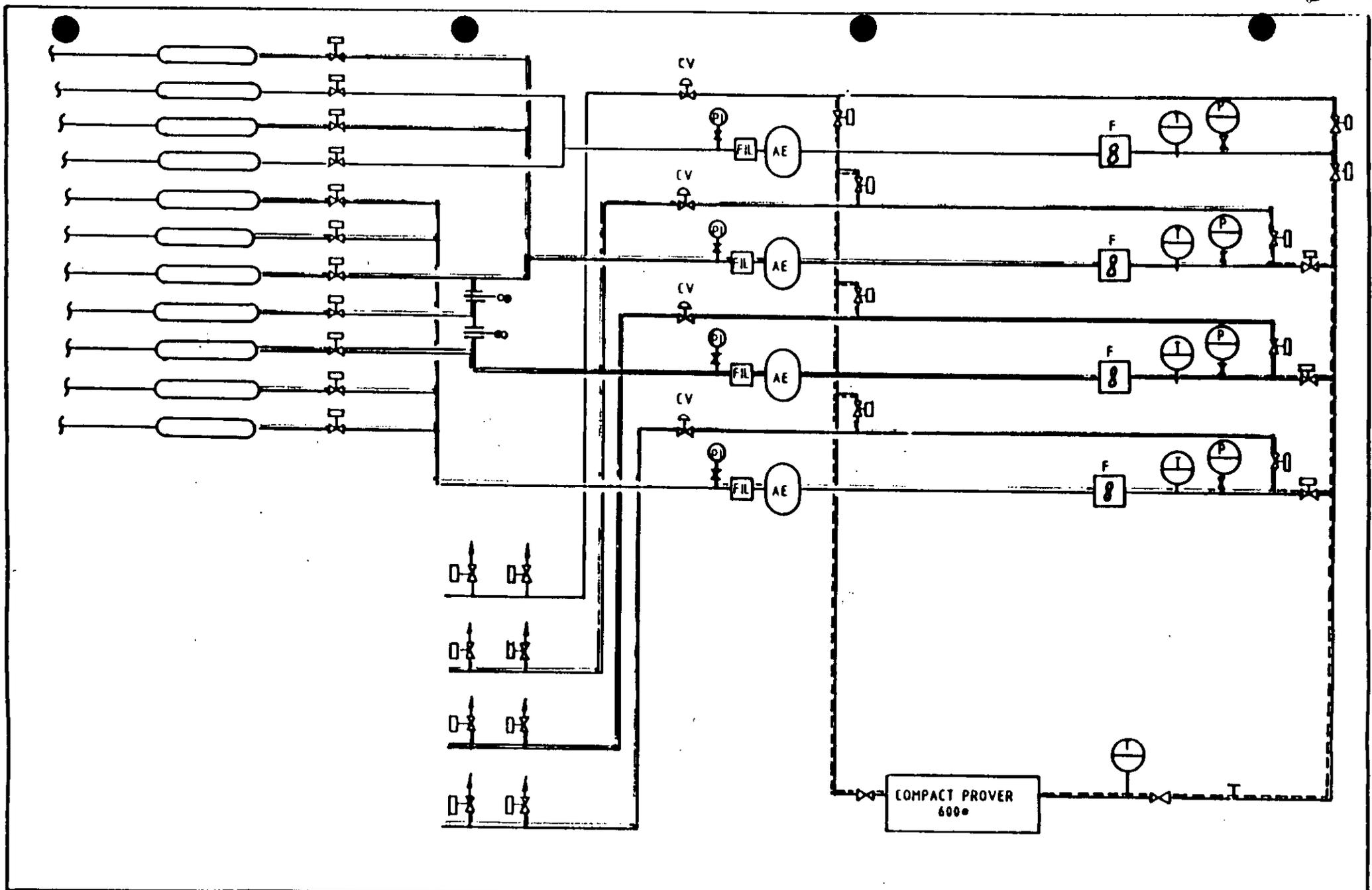
When designing the installation, it is essential to keep in mind the space requirement for opening the prover, due to the long instrument rod.

6.3 User training.

End users need a significant amount of training to operate the system with an adequate understanding. Despite a high degree of automation, data analysis needs a good understanding both of this system and proving techniques in general.

Maintenance of the system will also require a specialist, because of the complexity of the system.

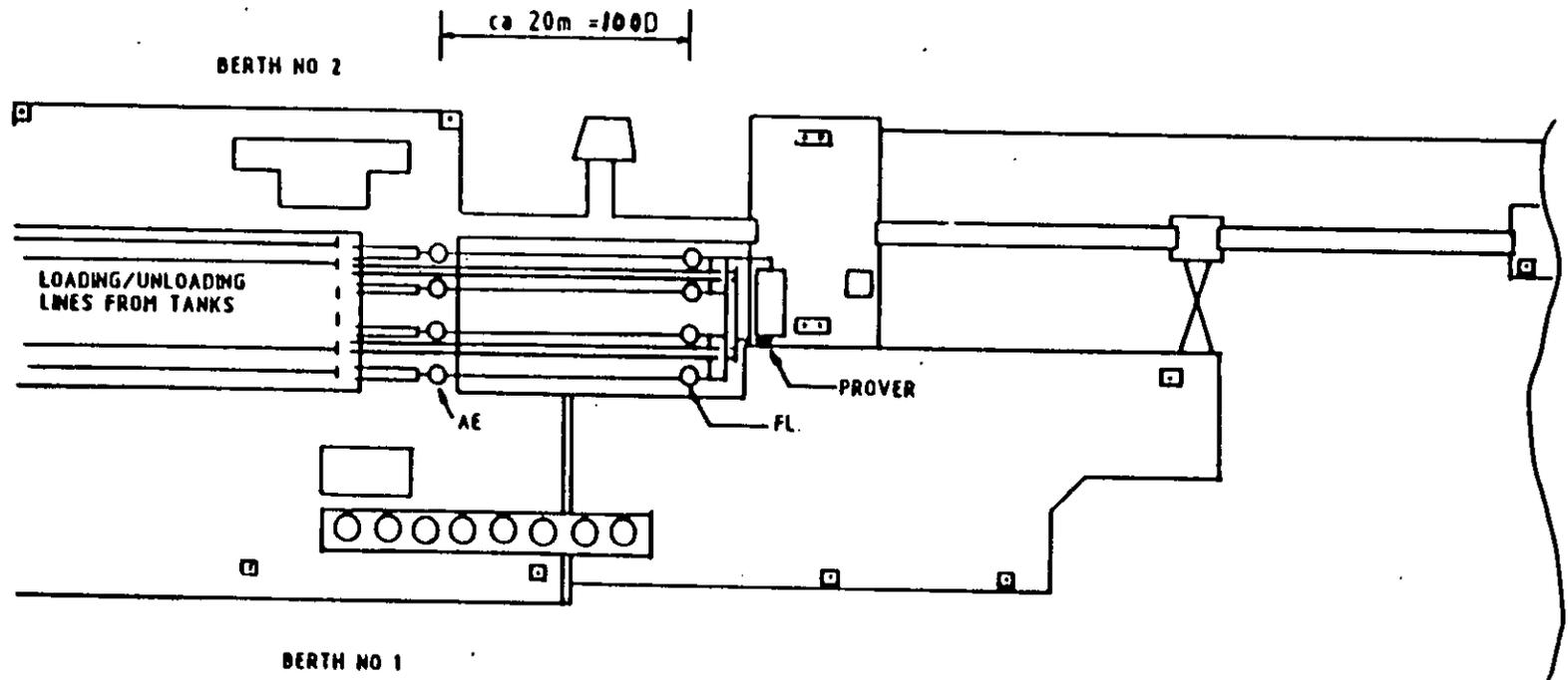




SLAGEN



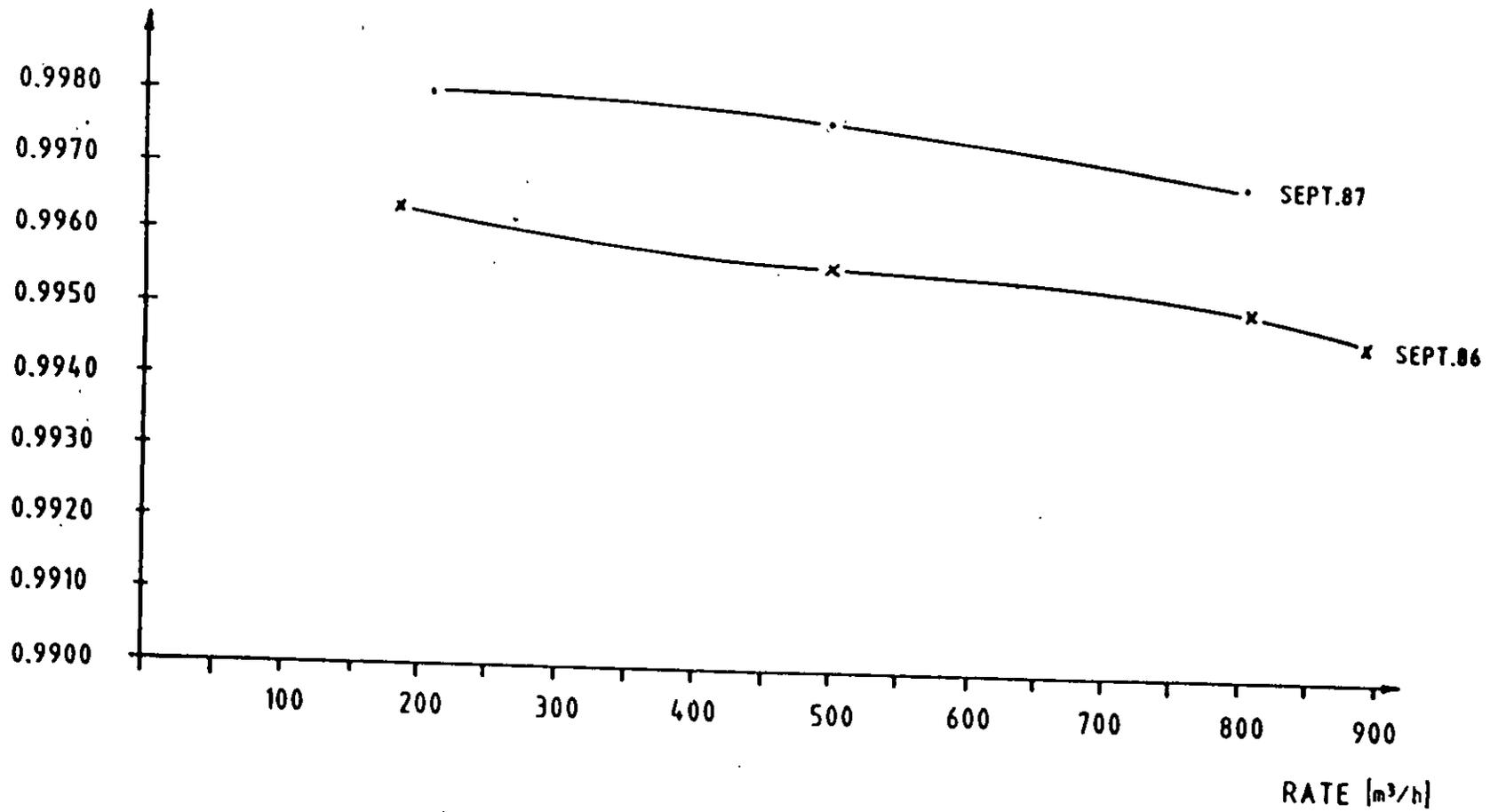
TURBINE METERS SLAGEN TERMINAL



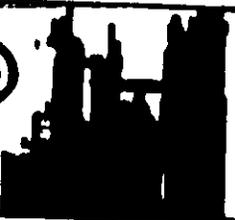
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TURBINE METERS PLOT PLAN

METERF.



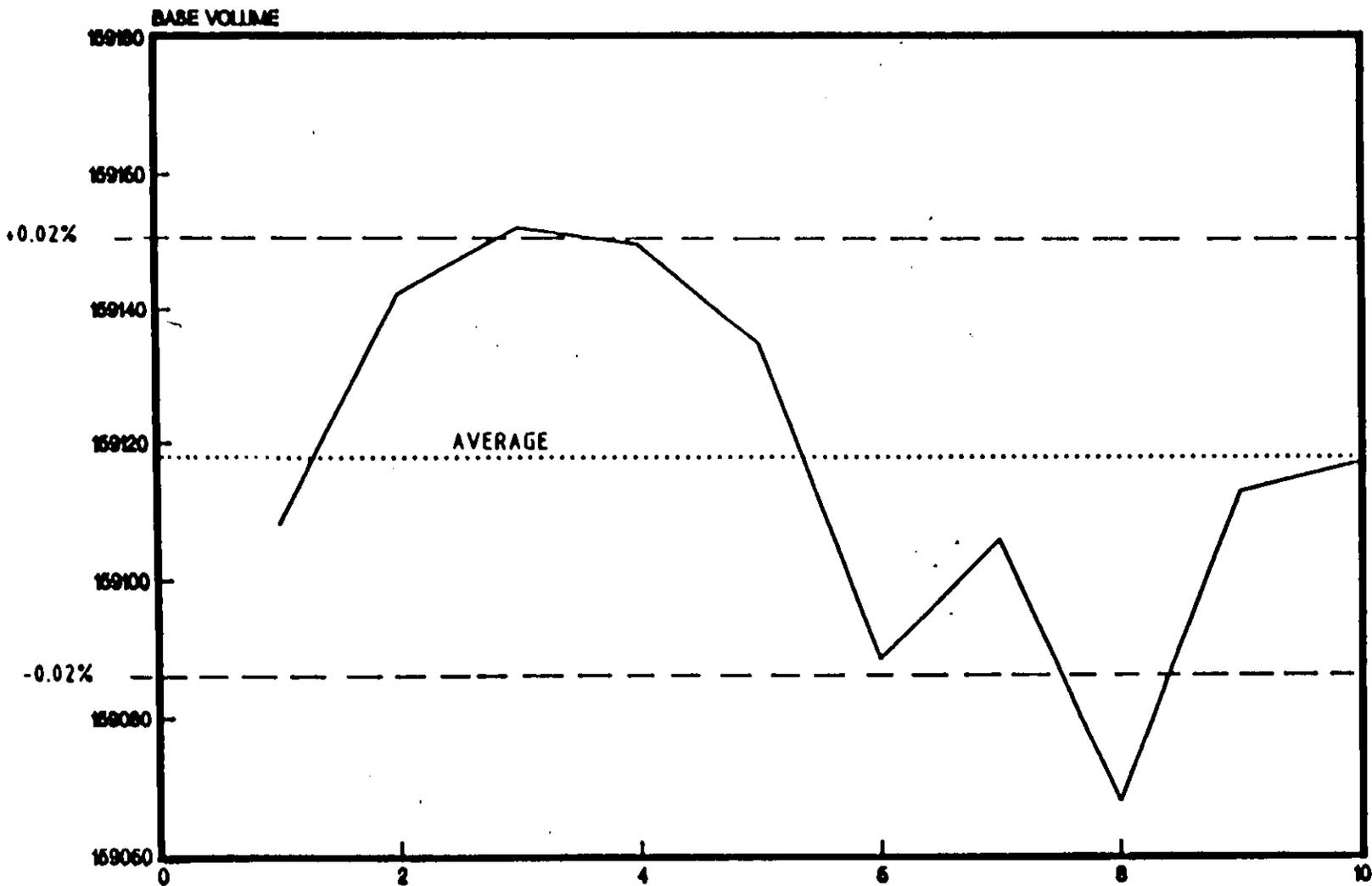
SLAGEN



CALIBRATION CHART

BASE VOLUME

MIDDEL



SLAGEN



CONTROL CHART, WATERDRAW CALIBRATION

NOV. 18 1986