300

LECTURES ON GEOTHERMAL ENERGY DEVELOPMENTS IN NEW ZEALAND

By

Derek Freeston,
Geothermal Institute,
Auckland University,
New Zealand

Presented at the UNU Geothermal Training Programme,
Reykjavík, Iceland, 7-10 September 1981.

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INTRODUCTION

When I met Dr. Fridleifsson for the first time at the UNU Standing Advisory Committee meeting on Geothermal Training at Pisa, Italy in November 1980 and tentatively asked whether I could spend some time in Iceland looking at the operation of the UNU course, I did not think I would be standing up here today as your third International Guest Lecturer particularly following such eminent "geothermalists" as Don White and Christopher Armstead. I feel very honoured to be asked to present this series of lectures and I only hope that my presentation might do justice to the position I am filling as the 1981 UNU Visiting Lecturer.

I thank you for this opportunity to visit your country and for your very warm welcome to me and my wife.

I propose first to say something about the organisation and work of the Geothermal Institute at my University and then discuss the status of Geothermal Energy Development in New Zealand through the eyes of one who is not involved or affected directly but who is keenly interested in the technological developments taking place at this time.

I would like then to present my work on two phase flow in which I have made a special study during the past 2 or 3 years, showing you some results and tentative conclusions and finally I intend to talk about some applications of this work and possibly hope there is time to introduce some of the project work undertaken by our students at the Geothermal Institute of the University of Auckland.

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1. A REVIEW OF THE DIPLOMA COURSE IN GEOTHERMAL TECHNOLOGY, UNIVERSITY OF AUCKLAND

1.1 Background

In 1975 the United Nations Development Programme (UNDP) in New York asked the University of Auckland to consider submitting a proposal for a training programme in geothermal science and engineering. In the first instance this programme was to cater for scientists and engineers from developing countries, and to cover techniques relating to exploration, exploitation, and utilisation of geothermal energy.

Following discussions between the University, New Zealand Government Departments, and the New Zealand Ministry of Foreign Affairs, a preliminary proposal was drafted to give a broad outline of training objectives and a tentative teaching syllabus. This document emphasized particularly the need for joint training of earth scientists and engineers, by way of common lecture courses, in order to eliminate any communication gap between these two disciplines during the exploration and development phases of a geothermal programme.

At this stage, UNDP organised a mission to visit a large number of developing countries with geothermal potential to assess the need for personnel training. The leader of this mission was Mr. J. Healy, formerly Government Volcanologist at the New Zealand Geological Survey in Rotorua. His report in 1976 indicated general support for the geothermal course and a requirement by some 16 developing countries for about 150 trained personnel over the next decade.

Following the recommendations of the mission a detailed proposal was submitted to UNDP and the New Zealand Government by the University of Auckland and in 1978 a contract was signed by the three parties to provide funding for the Geothermal Institute for an initial period of two and a half years with the first Diploma Course to begin in February 1979.

1.2 Organisation

The Diploma in Energy Technology (Geothermal) is offered as a full time postgraduate course over the months February to November. For students from developing countries UNDP Fellowships are available to cover travel accommodation, living costs, tuition fees and various other expenses connected with the course.

The Institute is organised with responsibility to the Auckland University Council and operates with a Director, two full time and one part time academic members of staff - supported by an Administrative Assistant, a Secretary and a Technician. A board of Studies with representatives from the New Zealand geothermal community, Government Departments and Private Industry, New Zealand Ministry of Foreign Affairs, UNDP and the University is responsible for the syllabus, selection of students and for identification of the specialist lecturers. A senior member of the Academic Staff acts as the UNDP Coordinator and Chairman of the Board of Studies

The lecture programme is given by about ninety lecturers from various Government Departments, Private Industry, and the University. In-course assessment, based on assignments and tests and written examinations taken towards the end of the course and a project form the basis of the award of the Diploma in Energy Technology (Geothermal), a pass in all papers is required.

The Institute is housed within the new Geology building where most of the lectures are held and where students and staff have offices. In addition the Institute uses a wide range of University facilities, laboratories etc., particularly in the Science and Engineering faculties.

Overseas students are housed in single study bedrooms in a University Hostel and are provided with full board. Recreational facilities are available on the University campus and include both indoor and outdoor sports as well as numerous activities organised on a club basis.

1.3 Course Structure

An overview is presented to all students in a series of lectures entitled "Geothermal Systems and Technology". This course paper consists of about 200 lecture/seminar hours spread over 20 weeks, the first 5 weeks being devoted entirely to this course. At week 6 the Engineers and Earth Scientists begin their specialist courses. For Earth Scientists "Geothermal Exploration for Earth Scientists" presents an intermediate level theory of the disciplines Geology, Geochemistry and Geophysics, and is taught during the period weeks 6 to 10. This is followed (weeks 11-19) by more detailed tuition in two of the disciplines for the paper "Geothermal Exploration Technology". Engineering students follow lectures for courses which are run concurrently (weeks 6-19) "Geothermal Production Technology" and "Geothermal Energy Utilisation."

All of these specialist courses comprise about 150 hours of lecture and laboratory time. The final part of the course, starting approximately in week 11, consists of a project in which students study some aspect of geothermal development, where possible, connected with their home country. A set of detailed notes is provided for each lecture. In all some 1500 pages have been issued to students. See Appendices 1.1 and 1.2 for details

Field trips totalling about five weeks are spent in selected geothermal areas of the North Island of New Zealand. Studies during these trips introduce students to geothermal measurement techniques, observation of exploration drilling and methods investigation of geological, geophysical and geochemical features related to geothermal systems and utilisation, both electric and non electric, of geothermal heat.

1.4 1979/1980 Course

The first course commenced in February 1979 with twenty-four students, nineteen of whom were UNDP Felllows from Chile, People's Republic of China, Ethiopia, India, Indonesia, Kenya, Nicaragua, Philippines and Turkey, and five came under the New Zealand quota. Of these two were sponsored by local industry and three came at their own expense. The group was equally divided between earth scientists and engineers.

Teaching and tuition during the course involved some 430 formal lecture hours, 200 laboratory and seminar hours and 230 hours spent on field trips.

At the conclusion of the first course the Institute sponsored the New Zealand Geothermal Workshop which took place at the end of October. Over 100 participants were present. Forty papers were presented over the three days of the meeting together with 23 poster papers presented by the students of the Institute. The proceedings, in two volumes (1), have been published and are available from the Institute and include, apart from the papers presented, some abstracted information from some of the students'work throughout the year as well as 1979 course statistics.

The 1980 course commenced with twenty-six students. The nineteen Fellows were from the People's Republic of China, El Salvador, Ethiopia, India, Indonesia, Mexico, Philippines, Tanzania, with seven New Zealanders, five of whom are sponsored (four by Government Departments and one by private industry) and two attended at their own expense. In 1981 4 students came from China, 5 from Indonesia, 4 from Philippines, 1 from Mexico, 1 from Turkey, 2 from Columbia, 1 from Equador, 1 from Kenya, 2 from Ethiopia, 1 from Tanzania, 2 from India and 3 were from New Zealand.

The course structure and material was the same, in general, as that used in 1979 except that a number of topics were blocked: e.g. Geochemistry and Drilling enabling a better integrated course together with a reduction in travelling time of visiting lecturers.

The number of visiting lecturers involved in the course was slightly less with the University taking a larger share of the lecture load. Field trips and projects were organised in a manner similar to the 1979 course.

The second N.Z. Geothermal Workshop was held in early November, 1980 with 30 papers presented and a good attendance, including many visitors from overseas, its success was assured. It is anticipated that the Annual N.Z. Workshop will be a regular feature on the Institute's calendar, a 1981 workshop will be held November 9th-11th at Auckland. In 1982 the Geothermal Institute will be the venue for the N.Z. Geothermal Workshop and 1982 Pacific Geothermal Conference to which it is expected participants will come from Pacific and S.E. Asian nations. Proceedings for these workshops are available from the Institute.

1.5 The Future

During 1980 a second training mission was undertaken during which an assessment was made as to the numbers of earth scientists and engineers required for on-going projects and future geothermal development. The findings of that mission which are reported elsewhere show there is ample evidence that there will be an accelerated demand for manpower trained in geothermal technology, and that the Auckland course can aid in making a significant contribution toward satisfying this demand. Support from UNDP, the New Zealand Ministry of Foreign Affairs and the University is such that the course will run in its present form until at least the 1984 intake.

In the future it is expected that the Institute will provide a centre for

Research. 1980 has seen three 1979 Diploma graduates return for further study and research. The permanent members of staff are themselves engaged in consultancy and research work. The University has extensive facilities which support these activities and the Institute provides a focus for geothermal research in both New Zealand and overseas.

The success of the course is due to many people, the lecturers, the back-up staff of the University and the many people throughout the geothermal community of New Zealand who willingly gave their time and expertise to help the Institute and its charges.

References

1. Proc. of N.Z. Geothermal Workshop 1979, Part 1 and Part 2, University of Auckland.
2. Proc. of NZ Geothermal Workshop 1980, University of Auckland.
3. Proc. of NZ Geothermal Workshop 1981, University of Auckland.

APPENDIX 1.1

Prescription

Part I All students

Geothermal Systems and Technology (86.100)

Scope of Geothermal Projects. Basic facts of geothermal systems. Introduction to geothermal exploration and technology. Reservoir Engineering. Chemistry of thermal fluids. Economic, environmental and legal aspects. Case studies.

Part II

Earth Scientists

(a) Geothermal Exploration for Earth Scientists (86.101)

Petrology, secondary mineralisation and alteration. Drill hole logging. Geochemistry of geothermal fluids. Geophysical investigation of geothermal fields. Estimation and assessment of thermal field potential.

and (b) Geothermal Exploration Technology (86.102)

Planimetric and geological mapping techniques, mapping and sampling of geothermal discharges. Geophysical prospecting techniques. Geochemical analysis. Drill hole logging techniques and instrumentation.

Note: The 86.102 paper can be divided into the three basic disciplines Geology, Geophysics and Geochemistry. The student chooses TWO of these for study.

Engineers

(a) Geothermal Production Technology (86.103)

Drilling techniques and completion tests, fluid transmission, thermodynamics and fluid mechanics of geothermal fluids, well operation and analysis, reservoir modelling and assessment, corrosion and deposition materials for geothermal plant.

and (b) Geothermal Energy Utilisation (86.104)

Applied thermodynamics, industrial, agricultural and domestic use of heat. Power cycles and electricity generation. Waste disposal, land erosion, subsidence. Environmental effects and impact report preparation. Development planning and costing.

Part III All Students

Project (86.606)

A written project on some aspects of geothermal energy.

APPENDIX 1.2

Programme Timetable

Middle February: Overseas students arrive: Orientation course - English classes, Industrial visits

Early March: Course Proper Starts.

Week 1 Field trip to Wairakei: Lectures/field visits. Includes inspection of hardware, demonstrations, geology etc. of Taupo volcanic zone.

Week 2-5 Lecture/Seminar/Laboratory on core course (86.100) for all students. Generally timetabled for mornings only 5 days/week.

Week 6-10 Specialist courses start

a) Earth Scientists - 86.101 Intermediate level course. Lecture/Laboratory/Field trips.

b) Engineers 86.103 and 86.104 run concurrently, Lectures/Laboratory with week 8 at Wairakei engaged in field measurement exercises.

c) All Students 86.100 lectures on Monday mornings, Friday afternoons for student seminars. Monday and Wednesday afternoons free for private study.

May Break: First week, field trip to Ngawha for exercise in compiling data for a prefeasibility report.

Two weeks holiday.

Week 11-19

a) Earth Scientists - 86.102 course, specialist topics in two of the three disciplines. Week 14 visit to Wairakei and Wellington for lectures/demonstrations at D.S.I.R. Laboratories.

b) Engineers As for weeks 6-10 with field visit to Wairakei for lectures/demonstrations.

c) All Students - 86.100 course continues as for weeks 6-10. From week 11 project topics are discussed with individual students.

Week 20 - Case Study Programme

Lectures finish

August Break: First week field trip to Rotorua, Kawerau, Ketetahi, Tarawera, etc.

Two weeks holiday.

September - October All students engaged on project work with final copy submitted for binding by the end of October.

November - During the first week students sit final examinations. Three examinations of three hours each.

The second week of November is allocated to the N.Z. Geothermal Workshop. Students participate by presenting their project work, either at a lecture or poster session.

An official closing of the course takes place at the workshop with presentation of certificates of attendance and course awards.

Note:

The Diploma in Energy Technology (Geothermal) is awarded to all students who have passed in all three parts of the course. Students who fail one or more papers will obtain a certificate listing those papers which have been passed.

During each lecture/laboratory course exercises are graded and are included in the final examination work.

2 THE NEW ZEALAND GEOTHERMAL SCENE

2.1 Introduction

The development of geothermal energy in New Zealand has been influenced, although not exclusively, by its potential for generation of electricity. Although the success of the Power Station at Wairakei generated confidence in geothermal energy as a power source the demand for electricity has been met by development of hydro sources and latterly by the installation of thermal stations based on the large gas field discovered off the South West coast of North Island in the late 1960's. The condensate from this field was attractive but was insufficient to justify the development of the field. It was necessary to exploit the gas and generation of electricity by gas fired power stations was adopted,putting a temporary halt on the development of other methods of generation.

However, over the last two or three years that policy has changed. Since New Zealand economy is geared like so many countries' to transport fuels, a new petro-chemical industry is growing which will use the gas as a replacement for liquid fuels; either as L.P.G., C.N.G. or as a base for methanol production. Government policy has also encouraged the use of indigenous energy resources for industrial purposes.

As a result of these changes, the development of geothermal energy has recently received support and the 1980 Energy Plan has programmed a new 100 MW Geothermal Power Station on the Broadlands field (Ohaki) to be commissioned by October 1986 and a tentative plan for a 100 MW station at Ngawha to be in operation 1991. In addition the industrial use of geothermal heat is being discussed in connection with a number of other fields in the Taupo-Rotarua Geothermal Region.

The research investigation and exploitation of New Zealand's geothermal resources is in general controlled by Government and their agencies, Ministry of Works and Development and the Ministry of Energy (NZ Electricity) with the Department of Scientific and Industrial Research (DSIR) providing the scientific backup.

Mention should also be made of the contribution to the world geothermal scene by the Private Sector of NZ industry. Two NZ Consultant firms are at present engaged on geothermal contracts overseas. Both companies started with N.Z. aid projects and have since expanded their operations. Kingston Reynolds Thom and Alardice (KRTA) are currently working in the Philippines and Canada and Geothermal Energy New Zealand Ltd. (GENZL) are working in Indonesia, Kenya, Ethiopia and the Azores. Both firms, apart from their own staff use expertise from the N.Z. Government departments and are able to offer a service for all stages of the development of a Geothermal Resource.

2.2 Current Status

As at March 31 1979, 5623.3 MW of generation capacity has been installed in N.Z. with an annual energy consumption of 22.000 GWh. The generation is shared between the two islands which are connected by cable, approximately one third in South two thirds in the North Island. In 1979 74.7% of total generation was from Hydro Stations and 25.3% thermal stations (geothermal, coal, oil and gas). Of these the 192.4 MW installed at Wairakei produced about 5.5% of the nation's energy consumption at an annual load factor of 97.92 per cent. The system is predominantly hydro with Wairakei being used as a base load station and fossil fuelled stations being used for peaking loads and for following the system load. For example the 5 x 120 MW sets at the gas fired station at New Plymouth operated in 1979 at an annual load factor of 64.67 percent with the gas turbine station at Stratford (4x 55 MW) at 27.25 percent. Whilst most of the hydro stations operated at an annual load factor between 35 and 70 percent with the exception of Manapouri (7 x 100 MW) which operated with a 89.26 percent load factor.

It is seen (Figure 2.1) that the known fields in N.Z. are mainly confined to the Taupo Volcanic Zone with the exception of the Ngawha field in the far North. Bolton (1982) has made an estimate of the potential of the major fields, Table 2.1 based on the volumetric method. Category A refers to fields that have been extensively developed or in which development will shortly commence, B to fields in which a number of investigation wells have been drilled, C to fields in which little or no drilling has been carried out. The point is made in this paper, that whatever reasonable assumptions are made in performing the calculations the potential geothermal energy resources available in the country, with current technology, is many times greater than the present N.Z. demand.

TABLE 2.1 (Bolton 1982)

ESTIMATE OF GEOTHERMAL ENERGY RESOURCES

Category	Field	Area km²	Max. Temp. °C	Heat Stored above 180°C	Potential Generation (Gwh) (Inj. Temp. 20°C)	Inj. Temp. 150°C)
A	Wairakei	15	271	6137	130,000	358,000
	Broadlands	11	307	6298	146,000	353,000
	Kawerau	12	287	5789	125,000	325,000
	Rotorua	10	250	3590	70,000	203,000
B	Ngawha	25	236	6482	113,000	363,000
	Tauhara	14	279	6240	135,000	359,000
	Waiotapu	12	295	6232	152,000	348,000
	Orakei Korako	6	266	2330	47,000	132,000
	Rotokawa	8	302	4410	104,000	256,000
C	Ruahine Springs	15	250	5358	108,000	311,000
	Waimungu	12	250	4308	83,000	242,000
	Reporoa	12	235	3050	54,000	175,000
	Te Kopia	6	240	1648	29,000	92,000
	To Kaanu	8	250	2886	56,000	163,000
	TOTALS	166	-	64758	1,352,000	3,671,000

These figures are used as a basis for the present investigation budget. An investigation drilling programme of about 16 wells per year is envisaged in order to evaluate the total resource in a 20 year period with a development time of 25 years. A two rig (large) operation is planned with an estimated (June 1980) annual budget of NZ$14.35 million (US$11.5 million). employing within Ministry of Works and Development (MWD) a staff of 103 (administration, design, engineers, scientists, technicians) and 163 construction workmen. The scientific support is estimated to cost NZ$ 1.25 million and is provided by Department of Scientific and Industrial Research (DSIR) requiring about an additional 30 staff at the Wairakei project office with considerable help from other divisions of DSIR estimated at about 23 manyears/year.

In August 1977 Government authorised the above investigation programme but in 1979 the programme was reduced to a "one rig" operation due to the state of the economy and the reduced electrical load growth. So that during 1979-1980 the investigation programme was based on 6-7 new wells drilled per year and a maintenance and workover programme in the operational fields. However, since the 1980 Energy Plan was announced late last year in which both new stations at Ōhaaki and Ngawha were included, it is anticipated that the "two rig" operation will be resumed.

2.3 Utilisation

2.3.1 Wairakei

Most people are familiar with the Wairakei Station and its history. In 1949 Government approved a 5 year investigation programme for the Wairakei area after which a drilling programme to obtain steam for 20 MW(e) was begun. 1953 Messrs Merz and Mclellen were appointed as consultant and proposed a 26 MW station to be extended to 56 MW if steam was available. About this time the UK Atomic Energy Authority became interested in using geothermal heat for the production of heavy water so a joint project was decided upon producing heavy water and generating electricity. In 1956 U K.A.E.A., because of a change in policy, withdrew and it was decided that stage one would be a station for 69 MW. Work began in 1956 and the first machine was commissioned on 15 November 1958. Stage two was approved in 1957 and the capacity was brought up to 192.6 MW which was completed in October 1963.

About 100 wells have been drilled and currently about 60 are used for production . Since 1964 the generation has been consistently around 1100 GWh per year. This has been despite a fall off in field pressures. The output has been maintained by an optimisation exercise which has resulted in an improved utilisation of the resource. To the present time some 8.9% of the total heat energy above 0°C is converted to electricity compared to 4.7% initially. However, in order to maintain station output it has been decided to connect three of the outlying wells to the production system which will add about 20 MW to the generating capacity. It is also evident that the H.P. (high pressure) machines are no longer fully utilised and they will be taken out of service.

The mechanical reliability of the station has been excellent with the annual station load factor around 90% having the best record for reliability of any station in the country. Some machines have run for around 120.000 hrs before reblading. Credit for this performance is in part due to the excellent work by the station personnel in maintaining the equipment.

Future work at Wairakei appears to be aimed at maintaining the steam supply. It is expected that new wells will have to be drilled. Work is also in progress to examine the use of reinjection as a means of waste disposal and possible subsidence control as it is likely that some restriction will be placed in the near future on the waste water discharge to the Waikato river.

2.3.2 Broadlands

As mentioned earlier, the 1980 plan calls for the development of the Broadlands field to supply a 100MW station to be known as Ohaaki by 1986. The probable final development could be up to 150 MW but the procedures allowing access, water rights etc. are now cleared for the first 100 MW. Authority to begin construction has been given and site clearance has started. The main features of the design will be the use of cooling towers instead of the river for condenser cooling and the use of injection for waste disposal.

Reinjection trials have been carried out at Broadlands over the past one or two years and while there are indications that the water could be injected at temperatures below the silica saturation temperatures there is sufficient uncertainty for the decision to be made that initially the injection temperature will be 150-160°C. One of the schemes being considered is to locate the Power station at the West Bank of the Waikato with relatively short (100-150 m) two phase transmission lines from the well sites to a number of flash plants sited in the field on both sides of the river, feeding two pressure steam to the station.

Main turbine inlet pressures will be 5-6 bars with pass in steam at 1.1 bar. At present the wells can discharge at pressures much higher than 6 bars but it is felt that rundown of pressure will occur and a proposal to use the H.P.machine from Wairakei on a temporary basis, is under consideration. If this was acceptable, 80 MW would come from the main machines and 20 MW from the H.P. sets.

In order to assess long term effects of accumulation of chemical species in a closed cycle condenser system a pilot plant was built at Broadlands and the controlling parameters established to assist the condenser design for Ohaaki. As a result gas disposal will be by means of a gas stack in the cooling tower, the gas being entrained in the cooling tower plume.

Over the past few years, steam from the Broadlands field has been used for drying lucerne or alf-alfa. The growing season is from November to April and the crop is harvested by cutting with a rotary mower, windrowed in the field, then gathered by a conveyor for transport to the drying plant. The crop has to be dried rapidly to retain vitamin A and protein and produce a hard pellet of a bright green colour, an important selling feature. The plant uses the steam from BR 27 about 500 m away which is reticulated to the plant via a two phase line to a separator close to the plant. The separated steam is piped into a finned tube heat exchanger through which air is forced to the drying chamber, the separated water being reinjected down BR7, a dry bore.

The Government financed the pipeline and the Ministry of Works and Development are responsible for the maintenance on wells and equipment. The existing dryer uses approximately 7 tonnes/hour of dry steam at 11 bar in order to raise air temperature to 124°C and produces about 0.75 tonne/hour of dried pellets. The operators of the plant, Broadlands Lucerne Company, have negotiated a price contract with the Government for the purchase of steam up to 18 tonnes/hr which would lift their hourly production rate, with some modification to existing plant and introduction of new driers, to about 2.25 tonnes of dried lucerne. The economics of this exercise are discussed by van de Wydeven and Freeston (1979).

2.3.3 Kawerau

Up to early 1979 the Tasman Pulp and Paper Co. had been operating the Kawerau field and had met the costs of installing and maintaining the field equipment. The original Geothermal Energy Act established that all rights to geothermal energy belonged to Government but allowed private persons to use the energy, provided they fulfilled certain conditions. In 1977 amendments were made to the act which made it more difficult for the public to develop geothermal energy themselves and perhaps more importantly gave the Government the right to develop a field solely for the purpose of selling geothermal energy. This means that effective control of a geothermal field is under one authority, the Government, and the value of geothermal energy for industrial purposes is recognised.

The major effect of this amendment was that the Tasman field equipment was purchased by Government and the maintenance and development of the Kawerau field became a Government responsibility (invested in MWD) the Government selling steam to the company.

At present the current demand is for 195 tonnes/hour of separated steam with further 75 tonnes/hour under discussion for a future expansion. The steam is used either directly or used through a heat exchanger to produce clean process steam. The surplus is used to generate electricity, a 10 MW turbine is installed on site. It is known that the field is capable of supporting a much larger usage than at present, the investigation drilling programme is just about complete. However the mill is located close to the production zone and it is necessary to assess the effects of increased draw off particularly with respect to subsidence. The paper machines are sensitive to differential movement.

The field equipment utilises conventional well heads delivering mainly by two phase lines to a Separator Flash plant in the field, from which HP and LP steam are derived. One of the largest diameter two phase lines in N.Z. is used here. It is 46 cm in diameter and about a kilometre long.

Paper manufacture requires substantial quantities of common salt. The mill is about 30 km from the sea and the idea of producing salt from sea water using geothermal energy is under consideration.

2.3.4 Ngawha

Seven wells have been drilled in this field. In general temperatures are low (236°C) but the area is large and two wells have given large flows. A third well drilled and tested early in 1981 did not appear to be quite so promising, however, the field is relatively unexplored and there is considerable interest both by the local power board and industry in the use of this prospect.

From the local power board's point of view, further load expansion in the area is limited by the transmission line capabilities through Auckland. There is no generation in Northland since the Marsden Stations which are oil fired were "mothballed" so unless these stations are converted to coal, power from the geothermal resource at Ngawha appears attractive. In addition Northland has extensive man-made forests and the timber industry will be expanding in the area requiring energy. As mentioned earlier the 1980 Government Energy Plan has included a 100 MW station on the field for 1991.

2.3.5 Rotokawa and Tauhara

These fields are relatively close to Wairakei, the former some 8-10 km distant where substantial deposits of sulphur occur. Private industry is keen to mine the sulphur using geothermal energy and discussions are in hand with Government for a joint venture. The Tauhara field is believed to have a connection with Wairakei so the draw off is being closely monitored, in addition the field extends partly under Taupo and the effect on the township is uncertain. However, some light industry is being encouraged to make limited use of the resource.

2.3.6 Rotorua

The geothermal area is confined to a North-South band running from Whakarewawera in the south to the lake edge in the North (Fig. 2.2). Surface manifestations mark the field, in all the area is about 10 km^2. The source of heat is a flow of hot chloride water rising near Whakarewawera moving northward towards the lake. The main flow mixes with a secondary flow from Pukeroa Dome. Both these are diluted by low chloride low temperature ground water in the west and north west. The deep hot water temperatures are cooled by mixing to give temperatures generally between 100-160°C.

The producing wells in Rotorua are shallow 60-120 metres with a few over 220 metres. Average well production is 0.38 MW thermal, which is sufficient to supply approximately 45 households. Approximately 4100 households (42% of Rotorua City) are located inside geothermal area and of these about 1100 (25%) use geothermal energy. In the commercial and industrial sector 340 use geothermal energy. The number of operating wells used by all sectors is about 421 (Lorentz and Mountfort, 1980).

In 1950s and 1960s geothermal energy was exploited by individuals for their own use. Since then rising costs have encouraged people to form cooperatives or group heating schemes up to 30 per group which operate successfully. However, capital costs are high, fees, maintenance, new equipment, soak holes, is usually many times more than alternative heating but the overall economics can usually be justified on the basis of running costs.

Since the energy is free, system designs, industrial and householder, tend to be very inefficient with a large wastage of energy and there is need for legislation to control this type of exploitation of what is a valuable resource. Geothermal District heating has been proposed but so far there has been little response from the community, mainly because Rotorua is a tourist centre which derives much of its income from the thermal manifestations of the area and which is concerned that these manifestations will lose their appeal if more drilling takes place.

It is only in recent years that the field at Rotorua has been monitored. A programme was recently introduced by DSIR for the joint implementation by the Ministry of Energy and Rotorua District Council and is intended to take at least two years before conclusions can be made which could be used to develop a management plan to the field. The objective is to ensure continuation of the natural activity at Whakawerewera. Meanwhile all drilling activity has been suspended.

2.4 Developments in techniques etc.

2.4.1 Drilling

Early drilling in N.Z. was carried out with 250 m and 500 m rigs however,most of the drilling has been done with 1000 m capacity rigs. Recently however the smaller rigs, because their operational costs are cheaper, are being used for reconnaissance drilling. Although the well is smaller in diameter and shallower it does provide positive information on which to base a decision for use of the bigger more costly rig.

Recently,use of the 1000 m rig has become necessary particularly where basement has been reached with little permeability and high temperatures. Drilling, looking for feeding fissures through the basement is then desirable.

Hydraulic fracturing is also a possibility which is being explored. Some preliminary trials using cold water from the Waikaito have been moderately successful.

Costs are variable and dependent upon local conditions but for 1980 costs Bolton (1980) gives

Depth	Production Casing	Approximate cost (NZ)
500 m	6 5/8"	<130.000
1000 m	8 5/8"	$400,000-$500,000
2400 m	9 5/8"	$650,000-$800,000

2.4.2 Disposal of Waste Water

A lot of effort has been put into reinjection studies particularly centred on the Broadlands field (Robinson 1979). Early tests were done by reinjection of water above and at production depth,in the centre of the West Bank (BR33) and which had been exposed to atmosphere This resulted in deposits in the well and recirculation in nearby wells. The average reinjection rate was 170 t/h and tests lasted for three months.

Next, reinjection on the eastern edge of the east bank (BR7) was tried. Water temperatures were between 105 and 135°C into a well that has a number of loss zones above and below the producing levels. This has resulted in an improved performance over a three year period. Average flow has been around

25 t/h with a well head pressure of 7 to 14 barg.

Reinjection into a well outside the producing field on the West Bank (BR34) with a good loss zone at 750 m into water at 60°C using reinjection water at a temperature of 95°C, required a relatively high well head pressure for a maximum flow of 215 t/h. Over a period of one month the well head pressure rose to 12 barg whilst the flow dropped to 160 t/h Pump failure stopped the test just as the pressures and flows were stabilizing but it was concluded that the test was unsatisfactory because of silica deposition in the rock.

Three short term tests (1 week) in three different wells on the West Bank (BR 13, 23, 31) having temperatures of 270°C at their loss zones received separated water which had not come in contact with air. Wellhead pressures ranged from 0 to 6 barsa. The pressures were falling in two of the wells with positive back pressures at the end of the test for water flows of around 200 t/h. Tests were stopped after a week to avoid permanent damage but were considered to be encouraging.

Further tests have been conducted by injecting into a high enthalpy (1600 kJ/kg) high gas (11% by weight in steam) well in the two phase region for long periods, however, the results are not known to the author.

In other tests chemical analysis combined with pressure transient studies of water injected at 100°C showed strong evidence of deposition close to the well. Other evidence suggests silica deposition is induced by calcite formed as a result of changes in CO_2/carbonate/bicarbonate balance as the water leaves the well. Other tests indicate that if cooling is done by heat exchanger without concentrating the solution rather than by flashing, then deposition may be suppressed.

However it appears that we do not have enough confidence yet to inject below the silica saturation temperature and Ohaaki is to be designed on that basis.

Chemical treatment of the waste water to precipitate out the silica was successful but resulted in large quantities of calcium silicate creating a problem. The material has a value and proposals are under consideration for manufacture of a small quantity.

2.4.3 Pilot Plant Studies

a. Condenser/Cooling Tower Tests

This was operated from 1978-1980. Direct contact steam condenser and associated water cooling systems were operated with a view to developing a gas separation and collection system to avoid the dissolution of gases such as H_2S and CO_2 in steam condensate. Condenser parameters which controlled the H_2S and CO_2 solubility were first established using once through cooling water. Subsequently closed cycle cooling water experiments were conducted to determine the species in the closed cycle system. In addition a series of corrosion probes were installed in the closed cycle system to assist with material selection for the full scale power station. A schematic of the rig is shown in Fig 2.3. of Glover (1979), Soylemezoglu (1980), Braithwaite and Lichti (1981), give the details.

The feasibility of disposing the gas in the cooling tower plume was demonstrated on this rig and will be used in the Ohaki plant.

b. Heat Exchanger

With the completion of the condenser tests the rig has been modified for a series of tests to collect data and demonstrate the use of geothermal energy in industrial heat exchangers. A programme of work using the rig and monitoring existing geothermal heat exchangers at Rotorua and Kawerau has started this year. The rig consists of 8 (tube in tube) heat exchanger tubes in series which are downstream of the separator on BR 22. The rig takes water/steam mixtures, the flow rates are monitored separately by orifice plates and gas content can be controlled. The tubes through which the geothermal fluid is circulated are approximately 5 m long and of 25 mm diameter. Temperature and flowrate of the cooling water can be controlled, a closed cycle system being used with the chemistry of the cooling water being continuously monitored. Instrumentation used is conventional thermocouples and water or water/mercury monometers. The thermocouple data is collected by a data aquisition system and analysis completed by computer. The intention,after calibration, is to obtain data of two phase heat transfer coefficients, fouling factors etc. to assist with industrial heat exchanger design. Corrosion monitoring is also being undertaken and different tube materials are programmed.

The rig was commissioned using single phase flows earlier this year and calibration data obtained. Two phase measurements have been underway for the last month or two.

2.4.4 Corrosion Work

An intensive programme of corrosion testing has been performed on the test bore at BR 22. Howard (1980) has built a vibrating reed facility for the study of corrosin fatigue in geothermal steam. This uses separated steam at 10 bar to excite resonant vibration in a reed specimen of test material. This technique enables fatigue endurance data to be accumulated more rapidly and with a higher degree of reliability than was possible using the conventional rotating bending technique. Turbine blade materials have been tested and one of the major conclusions of this and other corrosion work has failed to identify any turbine blade materials having substantial technical and economic advantages over the 13% chrome steel used at Wairakei.

Instrumentation for measurement and monitoring of corrosion rates has been developed and is used extensively for the corrosion investigations in N.Z. geothermal fields. Soylemezoglu et al. (1980) report a number of investigations using corrosometer methods and Lichti and Wilson (1980) describe methods using electrochemical techniques.

Two corrosion case studies are presented briefly below, the first involves the corrosion discovered on annual shut down (1977) in the HP lines at Wairakei. The occurrance, nature, mechanism, and preventive measures have been studied by many workers, see Sloymezoglu et al. (1980) for a review. Condensation pot model tests conducted by the author will be discussed in Lecture 4. The effect of condensate velocity and turbulence were considered to have a role in the pipeline corrosion mechanism. A corrosometer monitoring program, using condensate from a catch pot on the HP line which passed along a small diameter pipe, was used to measure these effects. Probes were exposed for 20 days and pipe sizes were changed to achieve a range of condensate velocities. Corrosion rates were shown to be a linear function of velocity (1.7 cm/s to 20.6 cm/s) demonstrating that reducing or limiting the flow of condensate would reduce pipeline corrosion rates.

The literature cited above, briefly indicates that the probable cause for the HP pipe line corrosion appears to be due to changes in fluid properties causing a reduction in the magnetite layer normally found on the inside of the pipe. Inhibitors were therefore tried to prevent the localised corrosion and the lines were monitored to demonstrate the effects. Fig. 2.4 shows these effects. The lower line shows the effect of exposing a carbon steel probe to pipe line conditions. After a surface layer had formed on the measuring section after 13 days, the rate reduced dramatically. Three inhibitors on the line were tried. The measurements for two of them are shown here, the third was bore fluid and indicated a similar result to the Trisodium tests. Trisodium has been adopted with an injection of about 0.5 kg/day wich has the effect of controlling the pH of the condensate to about 8.

The second case study is that of a corrosion survey of the materials used for construction of the condener cooling tower plant referred to earlier. Soylewezoglu and Lichti (1981). The survey included corrosion by the process stream as well as at atmospheric conditions. The chemical conditions within the process stream were extremely diverse and could not be defined explicitly and in addition the plant was aspirated intermittently with dismantling and modification to change experimental conditions, resulting in internal and surfaces being exposed to atmospheric conditions while wetted by fluids containing H_2S. Corrosion under these circumstances may have been more severe than that whilst under controlled experimental conditions.

The conclusions state that carbon steel is satisfactory for non-aerated steam operation, but unsuitable for environments where process fluids are airated.

Epoxy coatings were in general unsatisfactory.

Galvanized or painted carbon steel and stainless were generally resistant to atmospheric corrosion. Carbon steel and brass suffered extensive corrosion.

Stainless steel components located in cooling water and off-gas circuits had little or no corrosion and no stress corrosion cracking of stainless was observed.

2.4.5 Miscellaneous

a. Helical Screw Expander. In conjuction with USA,Mexico and Italy, N.Z. is taking part in testing the expander, using total flow. This will be in N.Z. during 1982 and the objective is to test the machine under conditions relating to water dominated fields using a condenser. This is an International Energy Agency project.

b. Downhole Spinner/Plate. Development and use of this device reported by Syms and Bixley (1979) is continuing. It has been used up to 280°C, providing a continous record at the surface of internal flows. It was used at Warakei to identify a 50 l/s downward flow in a well which has since been repaired and put back into production. Further work and application of these devices is described by Syms et al (1980).

c. Downhole Heat Exchangers and Separators. Simple 'U'tube typed heat exchangers are used in the home by many people particularly in Taupo. Recently some serious work has started in assessing and analysing their performance. One sizable installation has been installed at a school in Taupo to supply space heating and work at the University of Auckland has just commenced on the fundamental aspects of this type of heat exchangers.

Experiments are also in hand on downhole seperators although no details are yet available.

d. Computer modelling. An active group exists in N.Z. with people working in Auckland, Wairakei and Wellington.

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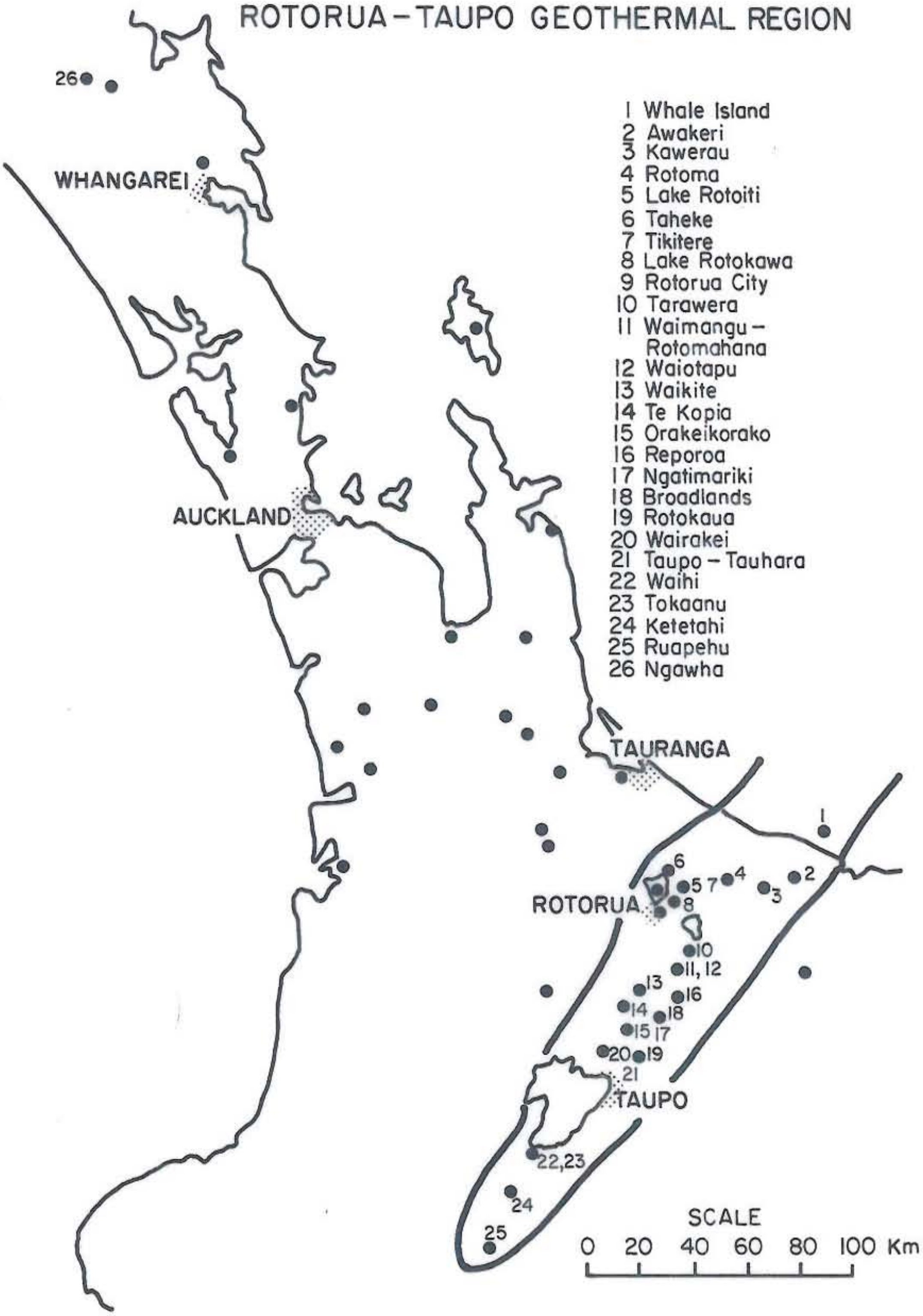

Fig. 2.1: Location of the thermal areas in the North Island, New Zealand. (Adapted from Department of Scientific and Industrial Research Report NZGS 38D New Zealand Geological Survey, 1974.)

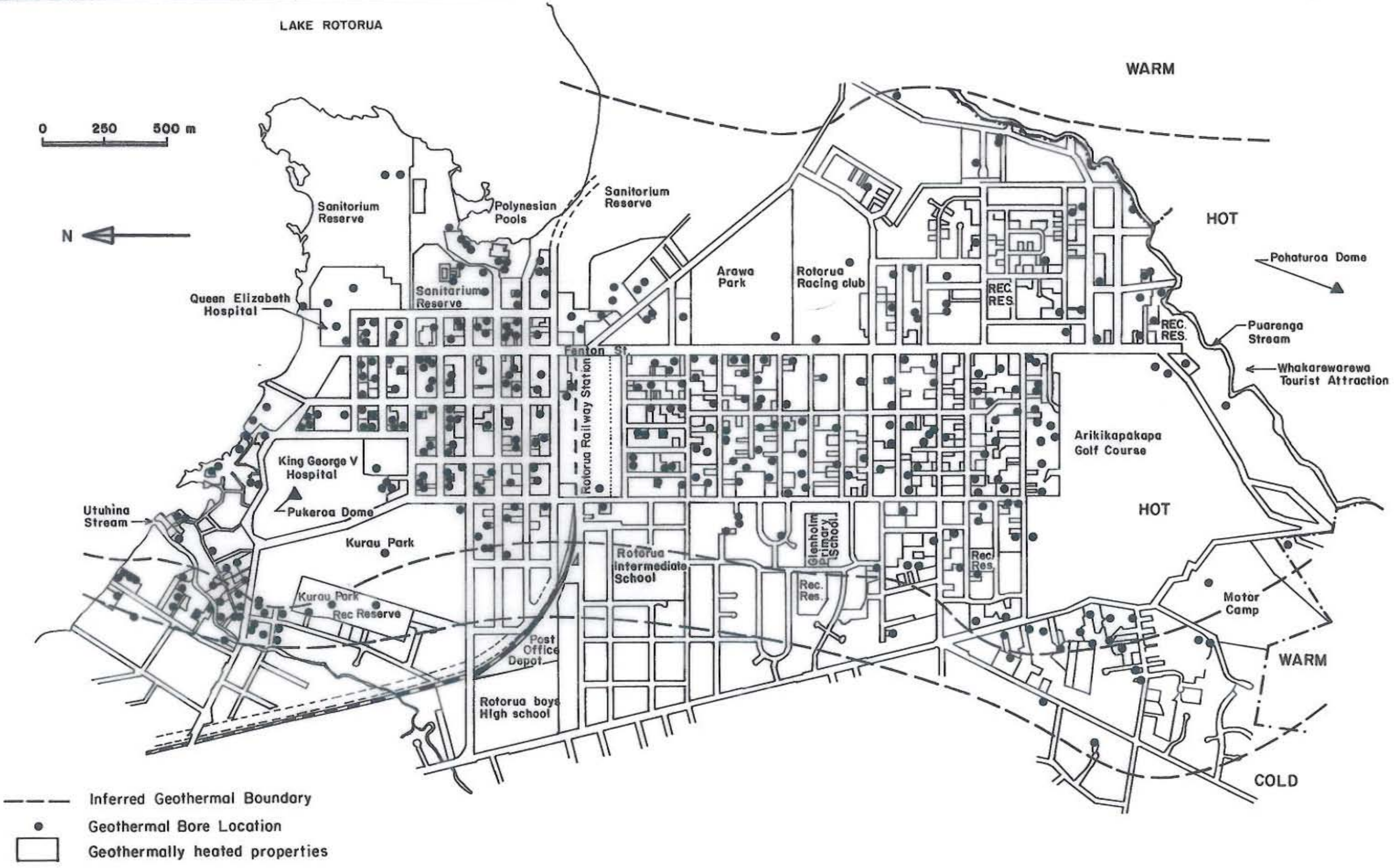

Fig. 2.2: Rotorua City geothermal area (Lorentz and Mountford 1980)

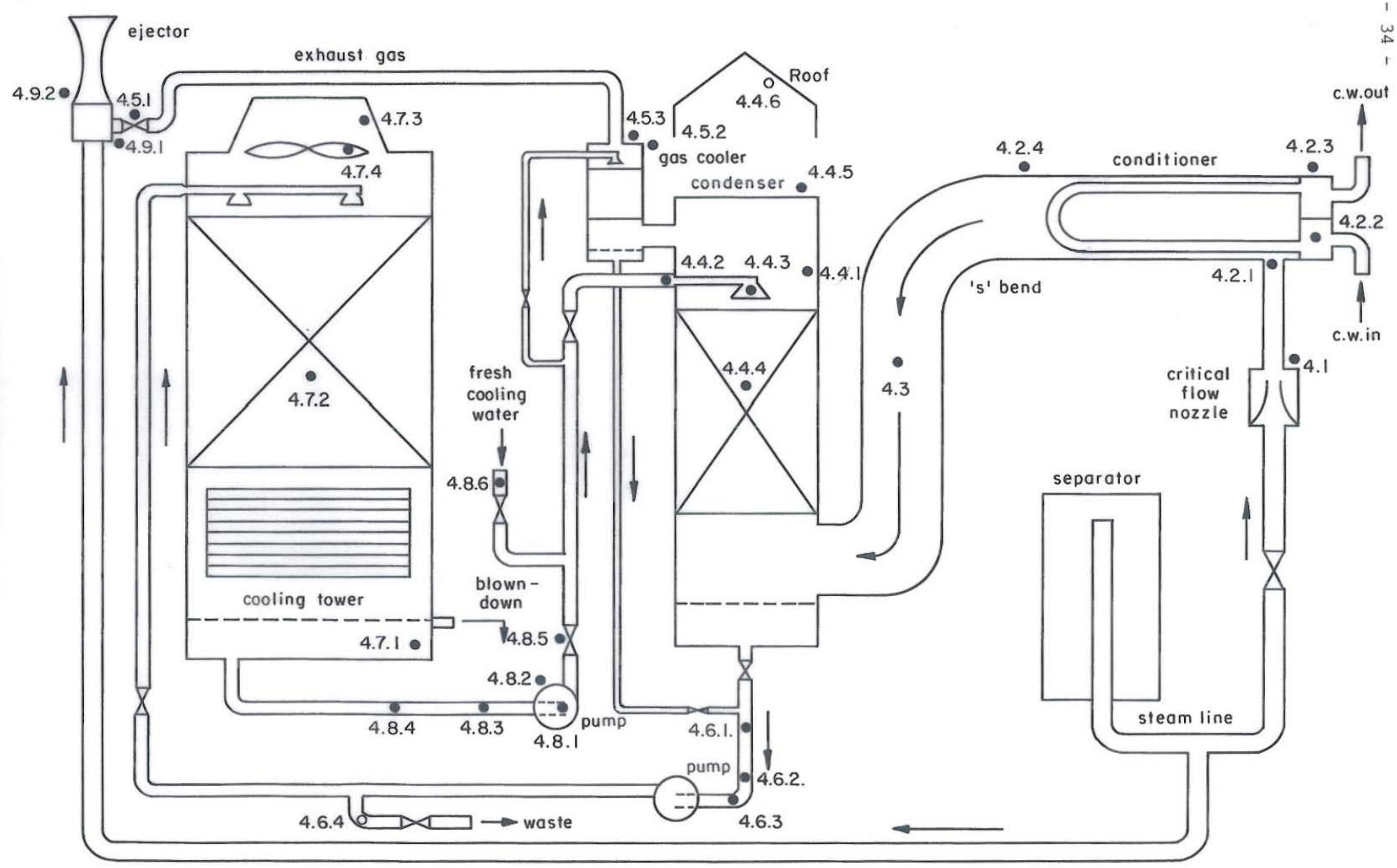

Fig. 2.3: Schematic representation of Broadlands/Ohaki Pilot Plant Corrosion Survey Locations

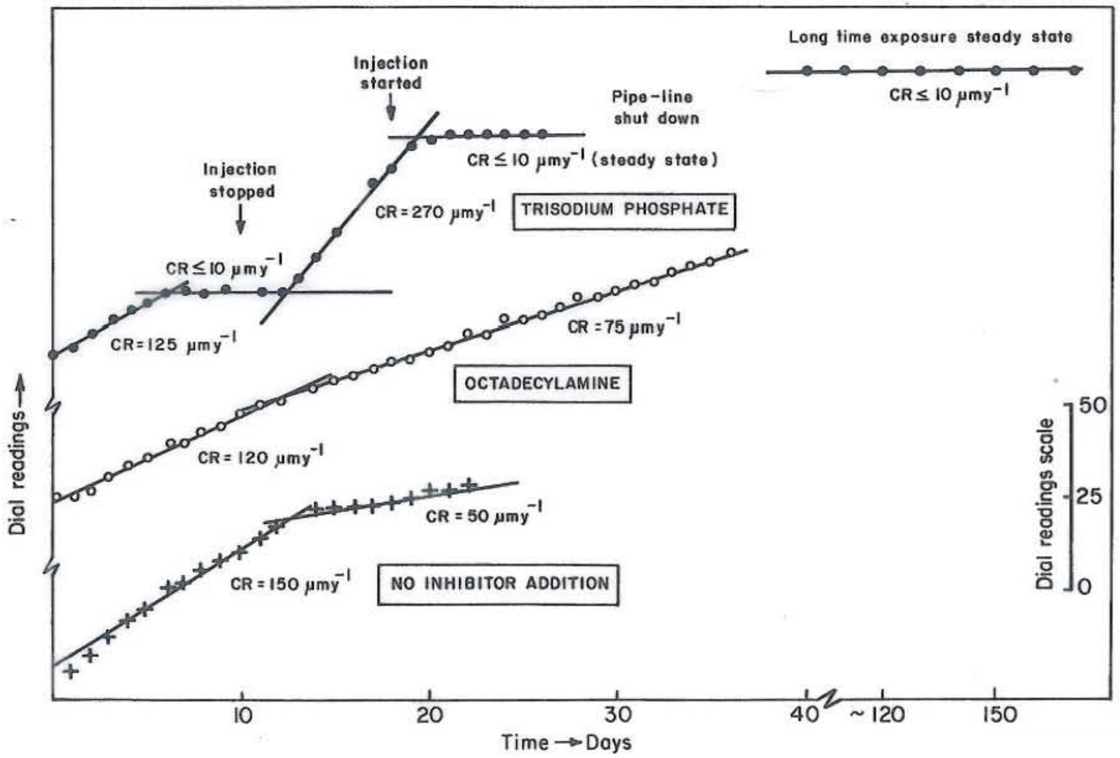

Fig. 2.4: Graphical presentation of Wairakei HP L-line corrosion inhibitor monitoring results. (Soylemezoglu et al., 1980.)

3. TWO PHASE FLOW RESEARCH

3.1 Introduction

The transmission of geothermal fluid from the wellhead to the user, for the generation of electricity or for use in an industrial process, has to be accomplished as efficiently as possible. The fluid collection and transmission hardware costs represent a significant part of the cost of development of a geothermal resource. It has been the general practice for wet geothermal fields to separate the fluid at the wellhead into steam and water phases, and to carry these fluids in separate pipelines. In connection with the generation of electricity from a geothermal heat source, James (1968) and Takahashi et al (1970) showed that by using two phase transmission there were economic factors and an increase in power obtainable from such resources which promised a significant overall reduced cost per kilowatt over a comparable single phase system. Recently James (1980) has postulated that two phase transmission of the geofluid would eliminate the steam condensate corrosion problem that has been discovered in the steam transmission line at Wairakei. Since these early papers, a number of two phase lines in various geothermal fields have been designed and commissioned, e.g. Kawerau, Tiwi and Tongonan (Philippines).

In order to design a safe and efficient pipe network for carrying a one component two phase mixture, data is needed describing the flow structure, the pipeline pressure drop, quality change and flow response to perturbations caused by various fittings and components. Demand for information for the design of nuclear power stations has been responsible for the great bulk of experimental work and associated correlations and models for steam water flow. However, experience has shown that descriptions of flow through relatively small diameter boiler-type tubes (up to 5 cm diameter) do not successfully predict the flow performance through large diameter (up to 1 metre) pipes that are encountered in geothermal applications. In addition, much of the data is for a two component flow, mainly air/water, which limits its usefulness in predicting the characteristics of a single component steam/water flow.

A test facility comprising a 10 cm diameter horizontal pipe loop was built on the Wairakei geothermal field at Bore 207. The experiment was designed to collect pressure drop data for typical geothermal steam/water flows through straight pipe and common components such as right angled bends, bends in 'S' and 'U' configuration and 'Tee' fittings. A short straight pipe capable of being tilted up to 90° was also available to investigate losses in inclined pipes. In support of the Bore 207, use was made of a laboratory air/water rig at the University of Auckland to investigate instrumentation techniques and assessment of some air/water data.

During the course of the project it was possible to make pressure drop measurements on the two phase pipelines at Broadlands and Kawerau.

This lecture, after a brief discussion of the two phase flow parameters and a description of the rig and measurement techniques used, presents some of the data collected in graphical form. This method of presentation has been selected in order to simplify the application to 'real' systems.

3.2 Two Phase Flow - General

3.2.1 Introduction

A number of reviews of the flow of a two phase mixture have been published which give detailed definitions of terms used, flow regime maps, and pressure drop correlations available.

The thesis of Nguyen (1975), Harrison (1975), Allen (1977), Lee (1978) and Chen (1979) are particularly relevant in this study. In addition, the books of Wallis (1969), Hewitt and Hall Taylor (1970), and Govier and Aziz (1977) give discussion of the methods of analysis, measurement techniques, and review of data correlations. A series of papers by De Gance et al (1970) discusses flow regimes, two phase heat transfer and the sizing of pipelines. This review gives detailed design techniques for both horizontal and vertical two phase flow with the emphasis on the practical problem solving of process plant situations. The Engineering Science Data Unit Items present methods for (a) calculating the pressure change in a system of known geometry carrying a known mass flow rate with a known heat transfer distribution; (b) calculation of mass flow rate in a system of known geometry with known inlet and exit pressures and known heat transfer distribution; and (c) the calculation of the I.D. of a pipe system of known length carrying a known mass flow rate and having specified inlet and exit pressures.

The basis of these methods is a data bank of some 2210 measurements obtained from the literature covering both one and two component adiabatic flows in both horizontal and vertical pipes over a range of pipe sizes, mass flow, etc. Seven established prediction methods for the friction component of pressure drop are compared with the data, and a statistical technique is established which enables the user to determine the best method for a particular problem. Suggested methods of calculating gravity and acceleration losses are also included.

Table 3.1 details the range of quantities used in the data bank, and, of the 2210 measurements, 47% were for single component fluids, mainly steam/water; the remainder were obtained in two component flows, mainly air/water. The maximum pipe diameter quoted is 30 cm; the majority of the measurements were obtained on pipe diameters of about 5 cm or less.

TABLE 3.1 (ESDU)

Extreme Values of Parameters

	Min. value	Max. value
Diameter (D) mm	1.0	305
Dryness (x)	0	1.0
Mass velocity (C) kg/sm^2	11	25000
Relative roughness (ε/D)	2.5×10^{-5}	5×10^{-3}
Gas viscosity (μ_G) NS/m	11.05×10^{-6}	22.7×10^{-6}
Liquid viscosity (μ_L) NS/m	74×10^{-6}	128000×10^{-6}
Gas density (ρ_G) kg/m^3	0.8	93.0
Liquid density (ρ_L) kg/m^3	612	13546
Surface tension (σ) N/m	6.2×10^{-3}	456×10^{-3}

A recent paper by Friedal (1980) represents the latest efforts known to the author in establishing the accuracy of the techniques for the estimation of pressure drop. Friedal presents a review of correlations, with their limits, for gravity and momentum as well as friction pressure drops. Their scope is defined and their accuracy for prediction is systematically compared with a new data bank. It includes extensive data during single component two phase flow of water and various

TABLE 3.2

Two phase system and zones of the void fraction measurements

Parameter	Single-component mixture	Two-component mixture
Mass flow quality (-)	<1	<1
Mass flow rate (kg/m^2hr)	4458 to 309	10330 to 3
Pressure (bar)	180 to 1	197 to 1
Density ratio (-)	1573 to 4	10710 to 5
Viscosity ratio (-)	23 to 2	5327 to 6
Diameter ($10^{-3}m$)	57.5 to 9.1	220 to 6
Surface tension ($10^{-3}N/m$)	53 to 2	469 to 25
Two phase mixture	H_2O	N_2/Hg
	D_2O	air/water
	R 12	air/oil
	R 113	argon/alcohol argon/water
Number of measured points	4161	4848
Horizontal flow	188	1350
Vertical flow	3973	3498
Number of authors or literature references	11	28

Two phase systems and zones of the frictional pressure drop measurements

Parameter	Single-component mixtures	Two-component mixtures
Mass flow quality (-)	< 1	< 1
Mass flow density (kg/m^2h)	8210 to 15	10330 to 5
Pressure (bar)	212 to 0.6	171 to 1
Density ratio (-)	1615 to 2	1194 to 6
Viscosity ratio (-)	46 to 2	5072 to 6
Diameter ($10^{-3}m$)	55.9 to 3.2	154 to 0.98
Surface tension ($10^{-3}N/m$)	69 to 2	80 to 20
Two phase mixtures	H_2O	air/water
	R 11	air/oil
	R-12	natural gas/water
	R-22	natural gas/oil
	R 113	nitrogen/water
	N_2	argon/alcohol argon/water
Number of measured points	6128	6740
Horizontal flow	1037	4706
Vertical flow	5091	2034
Number of authors or references	24	38

refrigerants, and of several two-component systems in horizontal and vertical unheated straight pipes under industrially relevant flow conditions. In addition, the accuracy of the prediction of some generally accepted correlations for void fraction is tested. In all, the data bank includes 9009 measurements of mean void fractions and 12.868 frictional pressure drop measurements in circular and rectangular flow channels by 39 and 62 different authors, respectively. A total of 18 relationships for the mean volumetric void fraction and 14 relationships for frictional pressure drop measurements were examined and compared. The ranges of the parameters are given in Table 3.2 as a function of type of two phase system. Of particular significance to this study, it is noted that the maximum pipe diameter for single component data is just over 5 cm, and 22 cm for a two component flow, air/water mixtures being prevalent.

3.2.2 Calculation Methods

Basically it is possible to distinguish three fundamental physical models. The HOMOGENEOUS flow model is the simplest. This assumes that the liquid and the gas or vapour are uniformly distributed over the flow cross section and in the flow direction so that the mixture can be regarded as a single phase flow with suitably defined mean values of the thermodynamic and hydrodynamic properties of the two phases. However, the meaningful definition of mean physical properties, particularly viscosity, of the two phase mixture leads to difficulty. The homogeneous flow model is frequently used as a reference.

In the SEPARATED flow model, or slip model, it is assumed that the gas and the liquid flow separately as continuous phases with distinct mean velocities within different parts of the flow cross section. A set of basic equations is formulated for each phase, the solution is closed by expressions detailing the interaction of the two phases and the interaction of the two phases with the channel walls. These are obtained from empirical equations which give the mean void fraction, defined as the mean proportion of a pipe's cross sectional area containing the gaseous phase, or the ratio of the mean velocities (slip) and the wall shear stress as functions of the primary parameters of flow. This model represents the other limiting case; the actual flow behaviour lies somewhere between the homogeneous and separated flow models.

More realistic representations of two phase flows has recently appeared in the literature. These models involve treating the various phase models independently, e.g. annular model, slug model, etc. The description of any flow pattern is generally accomplished by means of the statistical features of the flow or by means of mass, force and energy balances. However, the analysis is difficult, and only the relatively simple annular and stratified flows have been so analysed (Friedal 1980) . One of the problems with these models is that the classification of the various patterns is highly subjective; there is also considerable doubt in the establishment, quantitatively, of the patterns on a flow map drawn with respect to the primary parameters of flow.

A discussion of these models, with examples, can be found in the review papers and books quoted in the reference list.

During two phase flow in a non-horizontal channel the pressure drop per unit length is made up of contributions due to elevation (gravity) acceleration and friction, i.e.:

$$\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_g + \left(\frac{dp}{dz}\right)_a + \left(\frac{dp}{dz}\right)_f$$

The first two terms describe a reversible change of pressure; the frictional pressure drop , however, is an irreversible change of pressure resulting from the energy dissipated in the flow by friction, eddying, etc. The equations of the individual components can be defined by means of an energy or momentum balance. In the literature it is customary to use the momentum balance as the basic equation.

The pressure drop as a result of changes in elevation is given by -

$$\left(\frac{dp}{dz}\right)_g = \bar{\rho} g \sin \Theta$$

where Θ is the angle between the pipe axis and the horizontal. The definition of mean density ($\bar{\rho}$) is dependent upon the model chosen:

For homogeneous flows $\frac{1}{\bar{\rho}} = \frac{x}{\rho_G} + \frac{1 - x}{\rho_L}$

and for the separated flow model $\bar{\rho} = \alpha\rho_G + (1 - \alpha)\rho_L$ and a correlation for α is necessary. In general, void fraction correlations which are accurate for horizontal flow are invalid for vertical flows; however, no void fraction correlation explicitly attempts to correct for variations in Θ. At small mean void fractions and at large density ratios, the gravity component may be large. It is therefore important to have an accurate assessment of void fraction. For small changes in elevation the homogeneous model gives sufficient accuracy, and for a horizontal pipe this component is zero.

The ESDU Data Item 77016 attempts, using as a base seven wellknown vertical flow correlations, to calculate the effects of inclined flows using a conversion technique. Most other references recommend using either a suitable vertical or horizontal model depending on the angle Θ and its proximity to the vertical or horizontal plane.

During the flow of a two phase mixture through a pipe there is an increase in volumetric flow due to reduction in pressure caused by friction and, in a single component mixture, due to flashing. This results in an increase in the velocity of both phases with a resultant momentum change, giving a pressure drop due to acceleration. The addition of heating, resulting, for vapourising mixtures, in an increase in the vapour fraction giving an additional pressure drop due to acceleration.

An exact calculation of this component of pressure drop is not possible since a knowledge of local phase velocities is required, and again, a detailed knowledge of the flow pattern is necessary. One technique is to relate through a factor, the momentum multiplier, the momentum flux in a two phase flow to that of a single phase fluid. This relating factor is predicted using either the homogeneous or separated flow models (ESDU 78001).

Friedal (1980) states that the homogeneous equation leads in most cases to a more accurate or slightly conservative prediction. However in unheated two phase flows the pressure drop due to acceleration can often be neglected. If the ratio $\Delta p_{2ph}/p < 0.2$, where Δp_{2ph} is the frictional pressure drop and p the saturation pressure, then the acceleration component is probably negligible.

In general the frictional term contributes most to the overall pressure drop; however its calculation is imprecise with the result that many pipes and flow channels are over or undersized. Under comparable conditions the frictional pressure drop in two phase flow may be considerably larger than in single phase flow. Often the friction pressure drop in two phase flow is referred to that of a single phase flowing under certain hypothetical conditions. This relating factor is called the 'Two Phase Multiplier'. The various prediction methods use differing definitions for the reference single phase flow; for example, the liquid (or gas) phase flowing alone at the same mass flow rate as the liquid (or gas) component of the two phase mixture, or the liquid (or gas) phase flowing alone at the same mass flow rate as the complete two phase mixture. The determination of the frictional pressure drop or the friction multiplier is not possible by theoretical means alone; thus the developed models are corrected or correlated by measurements.

The literature contains numerous relationships and calculation models for the multiplier and friction pressure drop particularly in unheated small diameter tubes with single component flow, usually air/water. Generally they are based on relatively few measured values valid over a narrow range of parameters. Extrapolation outside this range, or application to other fluid systems, can lead to large errors in predictions. One of the favoured methods using the friction multiplier approach, particularly for the geothermal two phase experiments referred to earlier, is the Lockhart-Martinelli (1949) correlation. However this method has limited accuracy. James et al (1969) recommend the pressure drop estimated by this method should be increased by 30%, and Harrison (1977) tested the method together with others using the MWD file data (1965), and although the Lockhart-Martinelli method produced the best results, the predictions were on average 53% high. The standard deviation of data about this point was ±6% (corresponds to 65% of results lying within ±6% of the 53% high point).

Experimental investigations in transporting two phase geofluid has previously been reported by James et al (1969), Takahashi et al (1970), Soda et al (1975) and MWD file (1965) as reported in Harrison (1975). These experiments were all conducted in the field and represent the flow characteristics likely to be used in production plant. The range of values and test conditions are given in Table 3.3.

TABLE 3.3

	James (1969) et al	Takahashi (1970) et al	Soda (1975) et al	NZ MWD(1965)
Pressure MPa	0.52-0.83	0.21-0.25	0.28-0.59	0.47-1.29
Flow	12.0-52.4	5.3-15.7	13.6-44.2	12.6-50.7
Dryness	0.2-0.55	0.11-0.14	0.04-0.026	0.075-0.426
Diameter m	0.305	0.201	0.30	0.20
Test Rig	Horizontal 66.75m; U bend both horizontal and vertical 26.9 m.	Horizontal 23.85m; Inclined 7.41° 23.85m bends	Inclined 7° 200m (Transient tests)	Horizontal 15 Vertical 7.6m

3.2.3 Flow Pattern Maps

Many correlations for two phase predictions of pressure drop have been developed without consideration of the flow pattern. Since experimental data were used, effects due to flow pattern will be inherently incorporated, and this will sometimes result in correlation curves that behave in an unusual manner. Identification of flow patterns is subjective and is often dependent on being able to visualise the flow. Most of the flow pattern maps available have been obtained by study of the flow behaviour in transparent pipes and identifying regimes such as Stratified, Wave, Slug, Annular, etc. Other techniques used include X-radiography, which has allowed investigation in opaque channels with heated walls. Various types of probe have been developed which produce indirect information from which it is possible to deduce the flow pattern. Allen (1978) reviews some of these techniques.

A recent development by Matsui and Asimoto (1978) follows earlier work by Hubbard and Dukler (1966). This allows the identification of the flow pattern from the shape of the probability density function of a differential pressure signal. The presence of periodicities, the order of variance, and average value of the signal characterise the flow regime.

Several empirical flow pattern correlations have been developed but there is little agreement among them. A number of different coordinates have been proposed for the maps which, together with the problems of nomenclature and flow identification, produce a wide choice, and for a particular flow situation can give a range of answers.

The flow pattern map of Baker (1954) has found wide use over a long period, particularly in the petroleum industry. The ordinates are proportional to the mass velocity of the gas, and the ratio of the mass velocity of the liquid to that of the gas. Factors are introduced to bring the transition lines for systems other than air/water into coincidence with the air water system. This map was used by James et al (1969) and Takahashi et al (1970) to establish that the geothermal flows used in their experiments were in the annular flow regime. The apparatus of Soda et al (1975) provided for visual observation to enable the existing flow patterns to be compared with those predicted, and minor disparities were found.

Mandhane et al (1974), having resurveyed existing maps, introduced a chart based on a data bank of over 6000 points. The axes are in terms of the superficial gas and superficial liquid velocity; however, the data is predominantly air/water and is limited to relatively small diameter pipes. However, the authors noted the necessity of representing the transition boundaries as broad bands absorbing any property effects which may tend to shift the boundaries.

Taitel and Dukler (1976) carried out a theoretical analysis of the transition boundaries and demonstrated the effects of property and diameter changes in the location of these boundaries. Of particular significance for this study was the lack of sensitivity of the annular/slug boundary to changes in diameter, at least up to 30 cm, which was the limit investigated.

Vertical two phase flow is characterised by the symmetry of the flow patterns, which produces a different set of flow maps; the wave and stratified regimes of horizontal flow are not found.

With the two extremes, i.e. horizontal and vertical, showing differing regime maps, the inclined flow situation is extremely complex. Some preliminary work in this area has been reported by Spedding and Chen (1980) using an air/water rig. Frictional pressure drop data on axes of frictional velocity and total velocity are presented as discrete curves of superficial liquid velocity which also identifies flow regime. A series of graphs are presented illustrating the effect of pipe inclination for both up and downhill flows. (See Lecture 4).

3.2.4 Pressurelosses in Contractions, Bends, Tees, Valves

One of the least studied aspects of two phase flow is that of energy loss associated with such features as bends, tees, etc. These features occur in practical pipe runs and in sections of boilers and evaporators. One common way of calculating frictional losses in single phase flow is to express the resistance of the feature in terms of the equivalent length of straight pipe. The same procedure can be applied to two phase flows, although in general the equivalent length of pipes tends to be longer than for single phase.

There does not appear to be a generalised method of estimating losses in these features. Collier (1972) presents a short review of the data and techniques used. Evidently some authors recommend the homogeneous model as suitable for predicting the loss for expansions, contractions and bends, particularly for high mass velocities ($G > 2700$ kg/m^2s). It is reported by Fitzsimmons (1964) that the pressure drop round bends was up to 2.5 times higher than that predicted using single phase measurements and multiplying by an experimentally determined straight pipe multiplier. Chisholm (1967) expresses bend loss as a modified Lockhart Martinelli parameter for bends and tees. Valves are treated similarly in Chisholm (1967b); the data base is that of Fitzsimmons (1964). Govier and Aziz recommend using the equivalent length approach, using data for valves and fittings obtained from Crane Co., U.S.A., for single phase flow (Govier and Aziz, 1977).

Harrison (1975) used the availability function to analyse losses at pipe components (diffuser and sudden enlargement in geothermal steam water flow) and concluded that it was a more useful concept than the pressure recovery coefficient usually used in single phase flow.

Lee (1978) presents a more complete review of the literature on pressure losses in fittings, together with some experimental data taken on air/water rig for the 180 degree horizontal bend.

Of the experiments reported on geothermal pipe lines, Takahashi et al (1970) attempted to correlate measurements for separate 90° and 135° horizontal and 83° vertical bends in the 20 cm line on a pressure loss versus an apparent dynamic pressure based on a homogeneous model. Although three separate lines are drawn, the results are unconvincing since so few data points were available. James et al (1969) measurements on the expansion loop were correlated with mean dryness for the horizontal loop, but when the loop was vertical no such simple correlation was possible.

3.2.5 Methods adopted for presentation of measurements

3.2.5.1 Pressure loss calculation

Harrison (1975) developed a general one dimensional analysis of geothermal steam water flow in which the following simplifying assumptions are made: (a) The flow is one dimensional. Mean velocity components normal to the main flow direction are considered to be zero. (b) Turbulent fluctuations in the flow are negligible. (c) Pressure and temperature gradients normal to the main flow direction are zero.

In order to solve the resulting equations the flow is idealised by considering either a homogeneous or separated flow, as discussed earlier. From the earlier measurements on geothermal pipelines, flow conditions are in the annular-annular mist regimes and generally it is agreed that slug flow should be avoided. This enables further simplifications to the equations to be made and allows the separated flow model for low quality flows to be developed. Typically the dryness at the wellhead will be $0.1 < x < 0.3$. Correlations for wall shear stress, heat transfer, and void fraction are needed for the solution of the equations.

The prediction method developed by Harrison (1975) is simplified to allow manual calculation of pressure drop in straight horizontal pipe (Harrison 1977). For situations in which heat loss to the surroundings is small, the dryness of the flow can be considered constant. The total pressure gradient consists only of friction and acceleration components, and the one dimensional steady flow momentum equation reduces to

$$\frac{dp}{dz} = \frac{4\tau w}{D} + \frac{W}{A}\frac{d\bar{v}}{dz}$$

where τw is the wall shear stress.

With the assumption of annular flow and the consequent liquid film on the wall of the pipe, Harrison (1975) demonstrates that wall shear can be correlated in terms of the well known Moody diagram or one of the equations giving friction factor for rough pipes, the Reynolds number being defined in terms of the superficial liquid velocity.

The average liquid phase velocity is defined as

$$\bar{V}_L = \frac{W_L v_L}{A_L}$$

and by defining void fraction $\alpha = \frac{A_G}{A}$ and introducing dryness fraction

$$\bar{V}_L = \frac{W_L(1 - x)\ v_L}{(1 - \alpha)A} \qquad \text{------------------ } 3.1$$

Butterworth (1975) reviewed six well known correlations for void fraction and proposed that all could be expressed in a general form

$$\alpha = \frac{1}{1 + A\left(\frac{1 - x}{x}\right)^p \left(\frac{\rho_G}{\rho_L}\right)^q \left(\frac{\mu_L}{\mu_G}\right)^r}$$

A, p, q, r are arbitrary constants to be determined by experiment for the particular system.

For the typical pressure range used in geothermal pipelines, 5 to 12 bar, the viscosity term is near unity for r = 0.1 as listed by Butterworth (1975), and with A = 1 Harrison (1975) back correlated the data from the NZ MWD file (1965) to obtain

$$\alpha = \frac{1}{1 + \left(\frac{1 - x}{x}\right)^{0.8} \left(\frac{\rho_G}{\rho_L}\right)^{0.515}} \qquad \text{-----------} 3.2$$

This correlation neglects the possible effects of (a) flow regime, (b) inclination of channel, and (c) high mass transfer rates.

When the assumption of constant dryness and the concept of separate phase velocities is used, the acceleration pressure gradient can then be solely attributed to the density-pressure relation of the steam phase. The final dimensionless quantity is given as

$$AC = \frac{W^2 x^2 v_G}{\alpha A^2 P} \qquad \text{------------------3.3}$$

where P is the line pressure, so that the final equation for a horizontal pipe is

$$\frac{dp}{dz} = \frac{4\tau w}{D(1-AC)} \qquad \text{------------------3.4}$$

In most practical cases the acceleration term will be small.

3.2.5.2 Flow Pattern Map

The flow pattern map of Mandhane et al (1974) was chosen for this study. The map is based on a data bank of 5,935 individual observations over a wide range of properties for horizontal flow. Table 3.4 gives the range of parameters used.

This map is particularly easy to use since the coordinate axes are in terms of the superficial velocities. The original data was sorted by Mandhane et al (1974) to investigate diameter effects, and although the groups of data were small there was no observable effect for pipe diameters over 25 mm. Any effect that does exist is masked by being included in the calculation of superficial velocities. In any case, the work of Taitel and Dukler (1976) suggests that the annular-slug boundary, which is of major interest to this study, is unaffected by changes in diameter.

TABLE 3.4

Pipe diameter (mm)	12.5 - 165
Liquid phase density kg/m^3	704.9 - 1009.3
Gas phase density kg/m^3	0.801 - 50.46
Liquid phase viscosity kg/ms	$30 \times 10^{-5} - 90 \times 10^{-5}$
Gas phase viscosity kg/ms	$1 \times 10^{-5} - 2.2 \times 10^{-5}$
Superficial liquid velocity m/s	0.009 - 7.31
Superficial gas velocity m/s	0.043 - 171
Surface tension N/m	$24 \times 10^{-3} - 103 \times 10^{-3}$

The map as presented by Mandhane et al (1974) is based on air/water and to account for different physical properties the flow regime boundaries are shifted, not the axes as is common with many of the other maps. They found the effects of physical property change in the boundaries was surprisingly small.

The map and comparison with the Baker chart are discussed later.

3.2.5.3 Losses at Fittings

The equivalent length procedure has been adopted to present the pressure losses recorded at fittings. The straight pipe losses were first established as a function of the liquid phase velocity $\bar{V}_L$ (a best fit line is drawn through all the data); the measured fitting pressure loss is then converted by this curve to an equivalent straight pipe length.

3.2.5.4 Flow in Tees

For these components the single phase technique of presenting a loss coefficient in terms of a flow ratio was used. The loss coefficient is given by

$$K31 = \frac{\frac{\bar{V3}^2}{2g} + h_3 - \frac{\bar{V1}^2}{2g} + h_i}{V3^2 / 2g}$$

where h_i is the static head at point i, $\bar{V}_i$ is the mean velocity defined as

$$\bar{V}_i = x_i \bar{V}_{Gi}^2 + (1 - x_i) \bar{V}_{Li}^2$$

and $$\bar{V}_{GL} = \frac{xWv_g}{\alpha A}$$

For the fitting used, 3 refers to the upstream, 2 straight downstream, with 1 being the branch at right angles, that is, flow dividing from 3, into lines 2 and 1.

3.3. Experimental Apparatus

During the course of the project, measurements were taken on (1) a rig built on the Wairakei field at Bore 207; (2) on the 17.84 cm two phase line at the Lucerne Plant installation on the Broadlands field, and (3) the 48 cm two phase line at the Tasman Plant, Kawerau. In addition, much useful instrumentation experience was gained on an air/water facility built in the Aeronautics laboratory at the School of Engineering, University of Auckland. In general only the work on WK207 and the air/ water rig is discussed here.

The experimental rig at Wairakei was located on Bore 207 which is sited on the extremity of the field. It has a maximum output of about 20 kg/s at a wellhead quality of 20% and a pressure of 8.6 bar. The no flow wellhead pressure is 27 bar while the maximum operating pressure is limited by bursting disc to 17 bar. The two phase wellhead mixture is first separated in a conventional Webre cyclone separator, the water flowing into two holding drums at the bottom, with the steam phase extracted from the top of the cyclone. A schematic of the rig is shown at Figure 3.1. The 20 cm diameter pipes can take the separate phases to the two silencers as shown. Water is injected into the 20 cm steam line and allowed to mix before passing through a sudden contraction down to the 10 cm diameter loop. Flow rates are controlled by gate valves, and the two phases are metered separately by orifice plates before they are recombined.

The test loop consists of a 'U' bend and an 'S' bend configuration in which the spacer length can be varied. These are followed by a 45 degree 'S' bend combination. After a 6 m length of straight pipe a single right angled bend leads to a further 6 m of straight pipe before a long radius ratio, $^{R}/_{D} = 90$ segmentated bend. This bend is a model of the 46 cm diameter two phase line in use at the Tasman Co. installation at Kawerau.

A straight 18 metres long section ends at a tee, one arm of which goes to the horizontal silencer, the other to a straight section which was inclined at discrete angles of 21°, 44°, 66° and 90° to the horizontal and discharged to atmosphere through a lip pressure gauge. The rig is mounted 30 cm above ground level and is unlagged. The pipework and fittings are of standard steam quality and are butt-welded together, except at the combined bend section where flanges are used to allow the use of variable spacer lengths.

Instrumentation for measuring pressure for this rig was developed on the air/water rig built by Lee (1978). This consists of an 8.4 cm diameter perspex pipe arranged in the form of a 'U' bend. Since the objective of the Wairakei experiment was to obtain accurate pressure drop data, some time was spent on the air/water rig checking and developing pressure drop measurement techniques.

Hewitt et al (1964) report a technique using liquid purging of the pressure lines ensuring that the lines are always full of the liquid phase, gas filled lines having been found to be unsatisfactory.This method is suitable only for laboratory-type experiments as it is considered to be too complicated and not practical for field experiments. The position of the measurement point on the pipe circumference was also thought to influence the measurement of pressure. Adler (1977) suggested that pressure taps be placed on the horizontal centre line to avoid error induced by gravity.

For the field experiments, condensation pots on all tappings, which are placed on the horizontal centreline, are used to ensure that the line to the manometers are full of liquid. Models of these pots were installed on the air/water rig, and the technique for taking pressure measurements developed. Pressure purging was used as a standard, and the pressure distribution on complementary diameters on the pipe circumference compared at positions along the rig. The conclusions from these experiments show that the procedures to be used at Wairakei could be expected to measure pressure with an accuracy of better than 8%, which was considered satisfactory for the field experiment.

For all field tests static pressures were measured on calibrated Bourdon gauges. Specially constructed manometers were used for differential pressures; these were either mercury under water or compressed air inverted water manometers. As mentioned earlier, the phase flows were measured with British Standard Orifice Plates and differential manometers.

All results were recorded in the field and fed to the University computer for analysis. Programmes were written to provide the information in the format as presented in this report.

3.4 RESULTS AND DISCUSSION

In all, 255 separate runs were completed on the Wairakei test loop. In addition 14 data points were collected on the Broadlands pipeline and some further two phase data was obtained from the air/water facility.

Operating procedures were developed which ensured a wide range of parameters; however, a considerable time was necessary between test runs in order to allow steady conditions to prevail.

3.4.1 Dry steam tests

After commissioning the loop a series of test runs using dry steam established that the pipe's relative roughness was 0.001 to 0.002 which was typical of a 10 cm bore lightly rusted uncoated steel pipe (ESDU Data Item 66027). Figure 3.2 shows the experimental results; a best fit straight line is drawn through the data points. A further check on the roughness using dry steam was made 16 months later and confirmed earlier results: no significant change in roughness had occurred over this period.

3.4.2 Flow regimes

It had been established earlier that geothermal two phase lines should be designed to operate in the annular region. The flow parameters set for these tests explored the annular region and the transition between slug and annular. A number of test runs were recorded well into the slug region. In these cases, slugging flow was identified by oscillating manometer or pressure gauge readings and in some cases excessive vibration of the pipework. The supporting structure for the test loop, although adequate for an experimental rig, was not constructed as a production pipeline.

The range of the main flow parameters is given below.

Separator Pressure	6.5 to 11 bar
Steam Flow	0.47 to 1.74 kg/s

Water Flow	0.54 to 11.3 kg/s
Quality	0.05 to 0.33

Figure 3.3 shows the test data points on a Mandhane chart. The Harrison (1975) results and the Broadlands flow conditions are also plotted. Of significance is the large amount of test data taken apparently in the slug region. As stated earlier, both the Mandhane and Baker charts were constructed using air/water measurements. When the slug-annular transition line is modified for changes in physical properties by the technique suggested by Mandhane et al (1974) it appears as shown in Figure 3.4 . On this figure is shown the Baker slug/annular line. The points plotted are those which were positively identified as being slug flow. It is noted that the Baker line does not identify these points as being in the slug regime, even when the original air/water curve is modified for the effect of physical properties. The Mandhane chart identifies these data points as a slugging flow and shows that a number of the Broadlands measurements were also in this regime. This is not surprising since during the tests, although no large vibration of the pipeline was observed, there was the characteristic noise of a slug being transmitted down the line, and the plume from the silencer was noticeably 'puffing' at regular intervals. These conditions were within the broad band transition boundary region suggested by Mandhane et al (1974).

3.4.3 Horizontal Pipe Pressure Losses

The measured pressure gradient is plotted against the liquid phase velocity divided by the diameter of the pipe, in Figure 3.5. The pressure gradient is based on the pressure drop measured between tappings 50 to 54, a distance of 9.8 m.

The liquid phase velocity is determined using the separated model and the Harrison (1975) correlation for void fraction. A constant enthalpy determined at the separator pressure is assumed through the rig, the quality changing as the pressure drop occurs.

The Harrison (1975) prediction method as outlined in 3.2.5 is tested against the experimental measurements in Figure 3.6 and shows that the technique is reasonable.

In order to assess the Harrison method in comparison with others commonly in use, the experimental results for pressure gradient are plotted against those predicted for the Lockhart-Martinelli (Fig.3.7). The calculations for this method were carried out as recommended in the ESDU Data Item 76018 with an acceleration component included. It is seen that this method tends to overpredict the pressure gradient, and in general the correlation between measured and predicted is not good.

3.4.4 Pressure Losses at Fittings

All the results in this section are presented in terms of the ordinate showing an equivalent length of straight pipe. That is, the measured pressure loss across the fitting for a specified $\frac{V_L}{D}$ is referenced to the straight pipe losses as illustrated on Figure 3.5. The equivalent length in metres is given on the left hand axis, the equivalent length expressed in terms of a number of diameters on the right hand axis. Best fit straight line have been fitted to the data.

Figure 3.8 gives the losses through a 'U' bend and shows that the bend formed using a spacer length of two diameters gives considerably less loss than that using a ten diameter spacer. The air/water results of Lee (1975) support this trend. The results for the 'S' were not so conclusive.

The short radius 90 degree elbow (taps 30-40) and the tee (54-57) are compared in Figure 3.9, the tee showing the higher loss. This bend behaves almost as a mitred bend, which from single phase flow studies would be expected to have the higher loss. The comparison of these two curves illustrates how choice of bend affects losses.

Finally, the losses around the long radius mitred bend show an additional loss due to curvature. This extra loss can be significant at high liquid velocities. It is interesting to note that using a 90 degree elbow and lengths of straight pipe to achieve the change of direction between two points gives marginally less loss than the long radius ratio bend.

The measurements presented in this section demonstrate the magnitude of secondary losses. The pressure loss associated with each of the fittings tested is equivalent to a length of straight pipe of the order of 100 diameters, which is about twice that of single phase flow through the same fitting - Govier and Aziz (1977).

3.4.5 Comparison with Horizontal Air/Water Measurements

It is considered useful to make a comparison of the steam/water and air/water results to the same base. Data from two air/water experiments are analysed. One set is obtained from the experiments of Lee (1978) with an 84 mm diameter perspex pipe, the other from Chen (1979)who used a 45.5 mm diameter perspex pipe. This latter rig was fitted with quick action valves which enabled mean void fraction to be determined experimentally. Figure 3.10 shows the steam/water curve obtained at Wairakei and the air/water results from the two experiments. Only annular flow data was included from Chen (1979) and the experimental void fraction measurements used to determine V_L. Clearly the separated model correlate the air/water data, and there is reasonable agreement between the two sets of air/water information. However , the air/water measurements underpredict the steam/water gradient.

In Figure 3.11 the experimental void fraction of Chen (1979) is compared with the void fraction correlation of Harrison (1975) for this particular air/water experiment. There is a divergence, particularly for the lower values of void fraction, generally corresponding to low quality. This indicates larger quantities of water with increasing wall film thickness, with subsequent changes in flow structure at the interface. Of course by using a Butterworth type void fraction correlation, with indices fitted to suit the air/water results, experiment and prediction can be made to agree, which is what Chen (1979) has done.

In addition to the above differences it should be noted that the steam/water results were obtained for a rough pipe, i.e. relative roughness of about 0.001, which for a fully turbulent liquid Reynolds number would give a friction factor of about 0.022. The air/water data was obtained for a smooth pipe with a friction factor of about 0.009 over the range of Reynolds number tested. The separated flow model shows pressure gradient to be proportional to friction factor, ignoring the acceleration component for a given set of flow conditions. It could therefore be expected that the smooth pipe gradient for a given $\frac{V_L}{D}$ would be increased in the ratio $\frac{0.022}{0.009} = 2.4$. This moves the air/water data above the steam/water curve. However, more information is needed before such detailed conclusions can be drawn.

It is suggested from this discussion that care should be taken in using air/water correlations for steam/water calculations, and secondly, that effects of roughness should not be ignored.

3.4.6 Conclusions

The main conclusions are that

a) the separated flow model as developed by Harrison can be used within confidence to predict pressure drop for a two phase flow in horizontal pipe within the range of the parameters tested.

b) the Mandhane Chart is satisfactory in predicting the annular/slug transition region

c) it is clear that a lot of experimental data has been collected which requires further analysis. Care should be taken in using smooth pipe air/water data for prediction of pressure losses.

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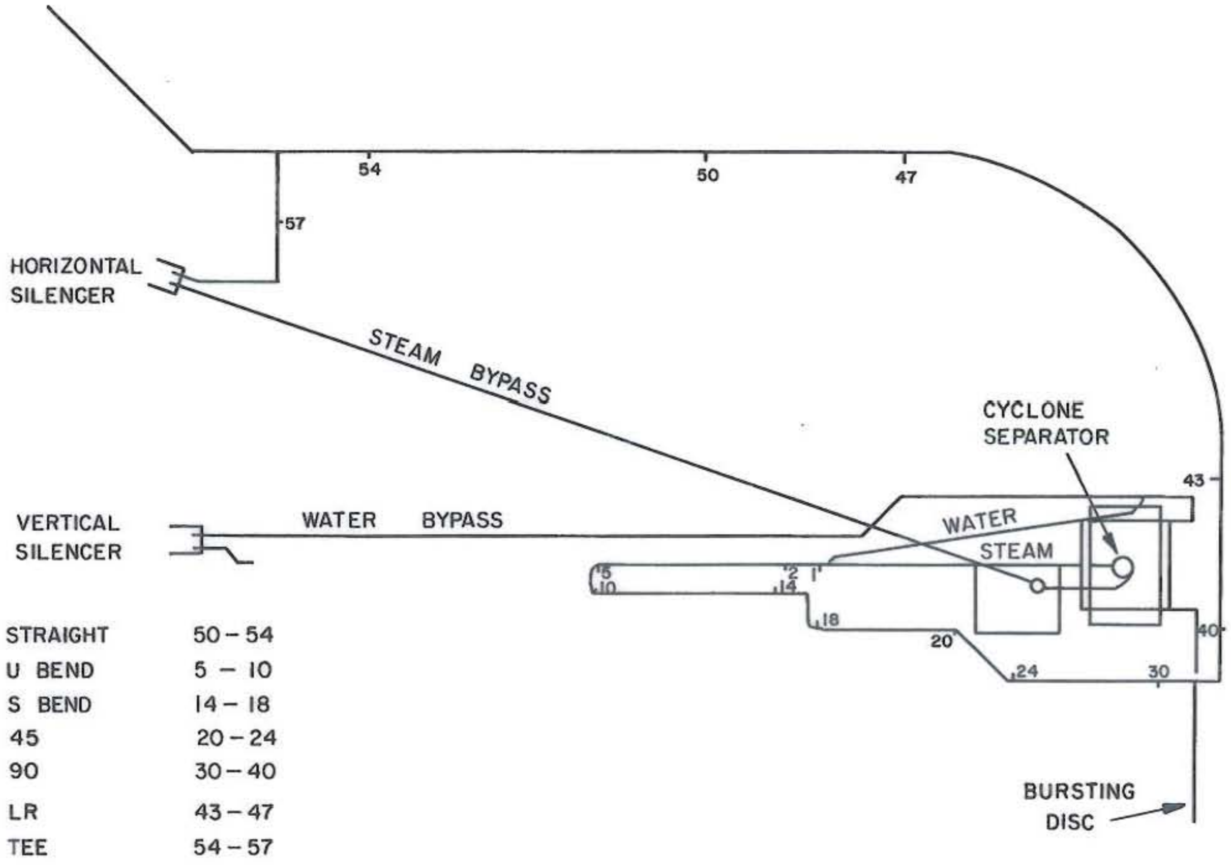

STRAIGHT	50 – 54
U BEND	5 – 10
S BEND	14 – 18
45	20 – 24
90	30 – 40
LR	43 – 47
TEE	54 – 57

Fig. 3.1: Schematic of Wairakei Test Loop

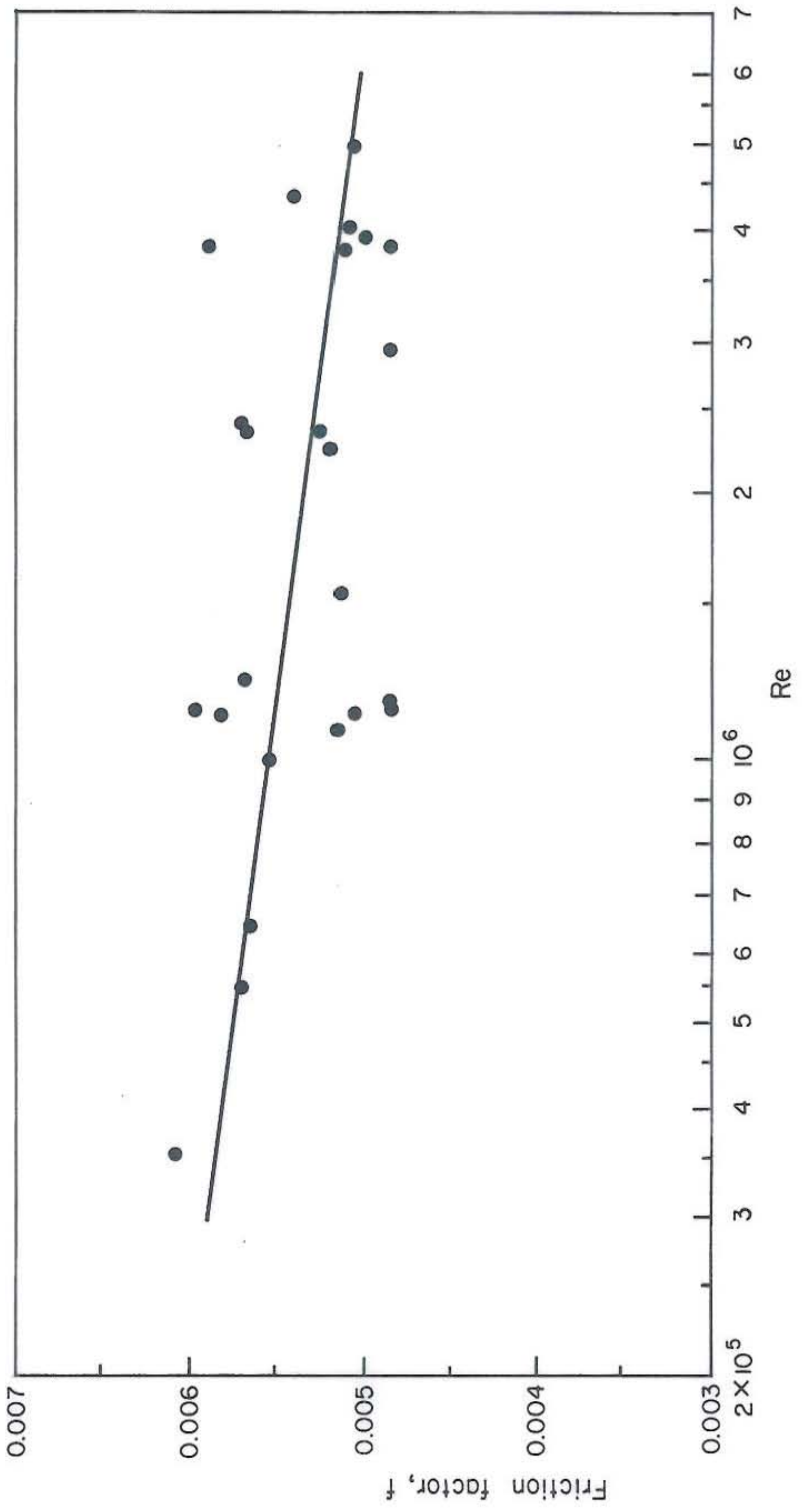

Fig. 3.2: Friction factor versus Reynolds number for dry steam flow

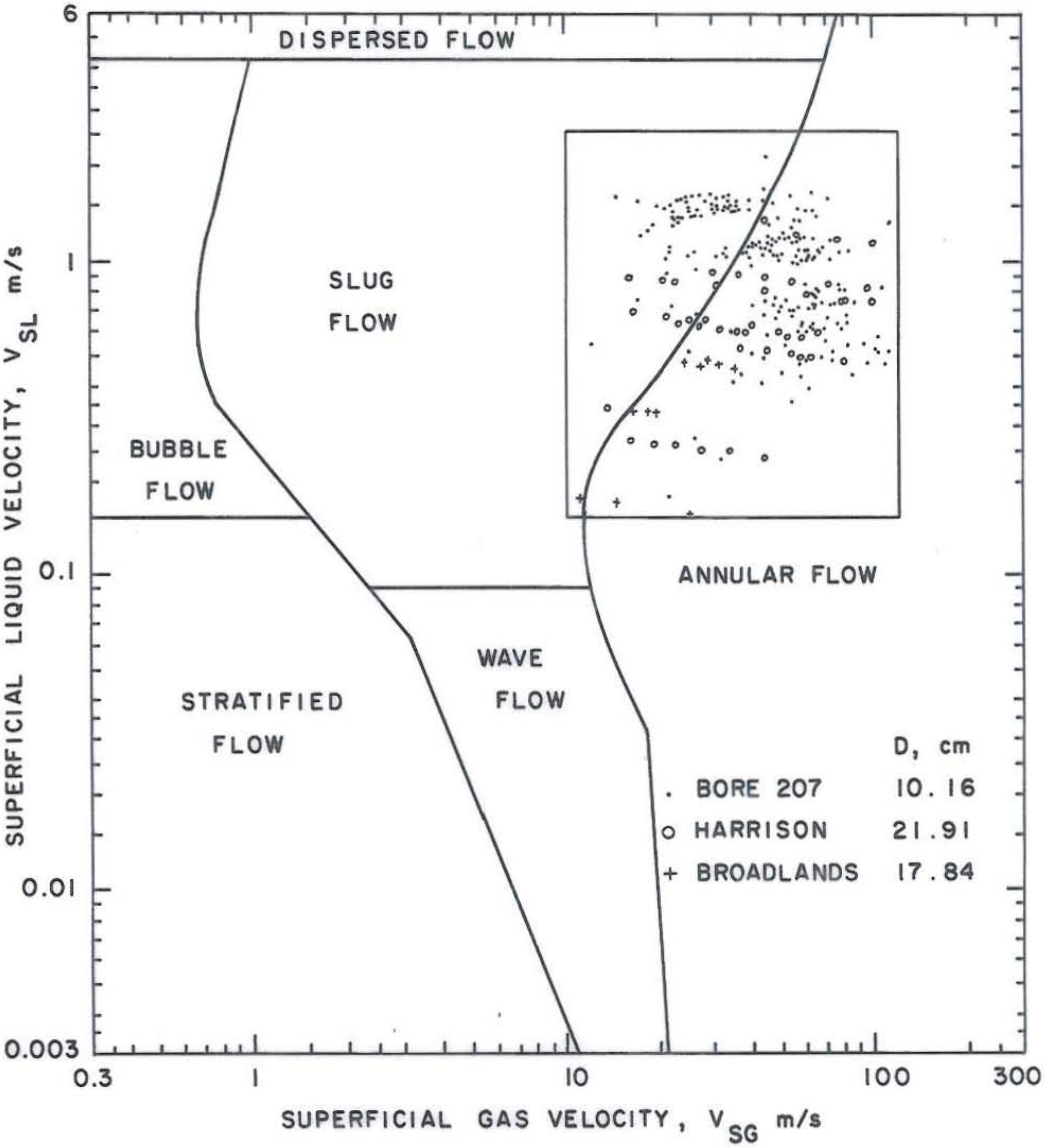

Fig. 3.3: Flow pattern map of Mandhane et al. (1974) with flow data

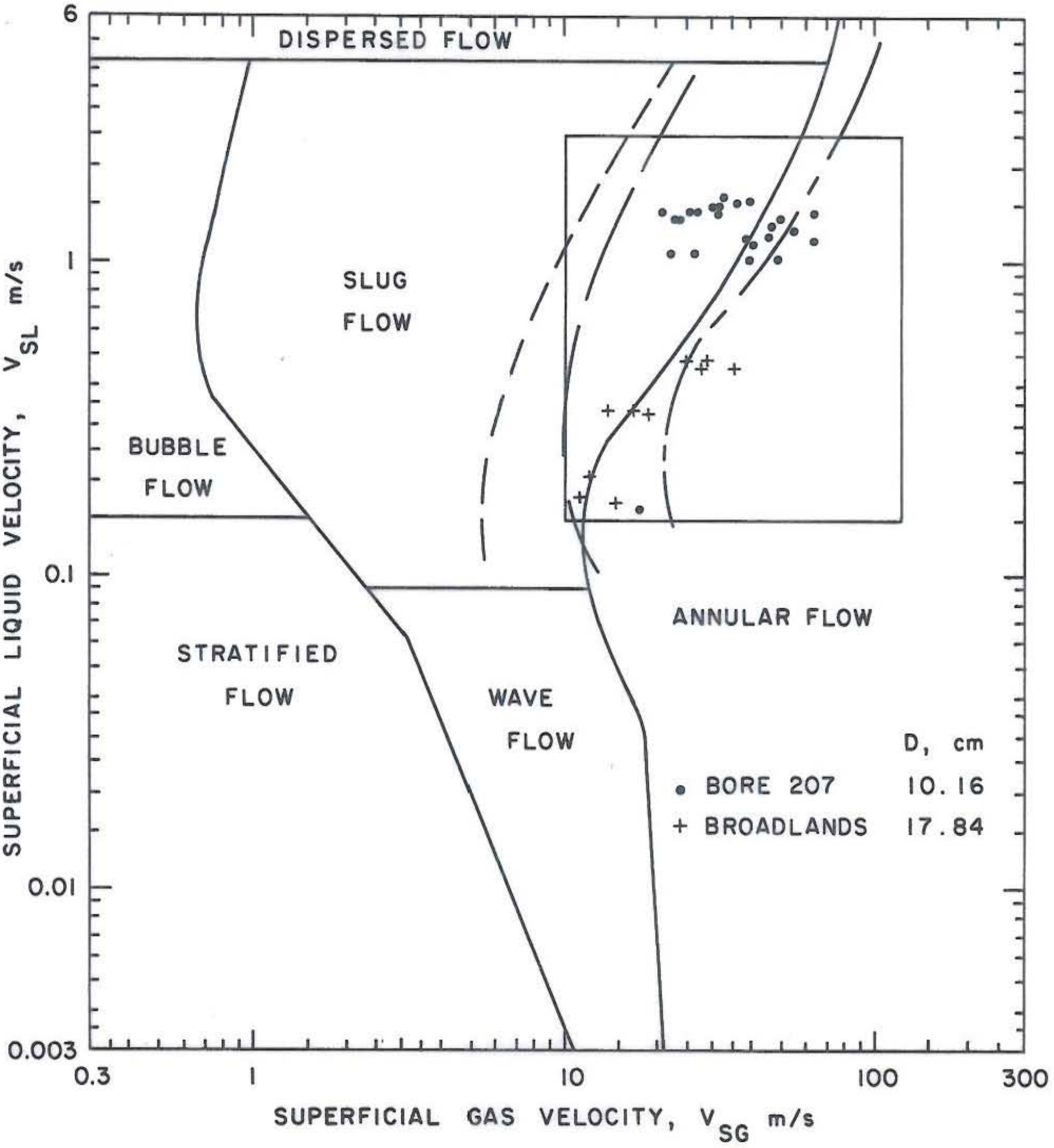

Fig. 3.4: Slug flow data plotted on Mandhane et al. (1974) flow pattern map

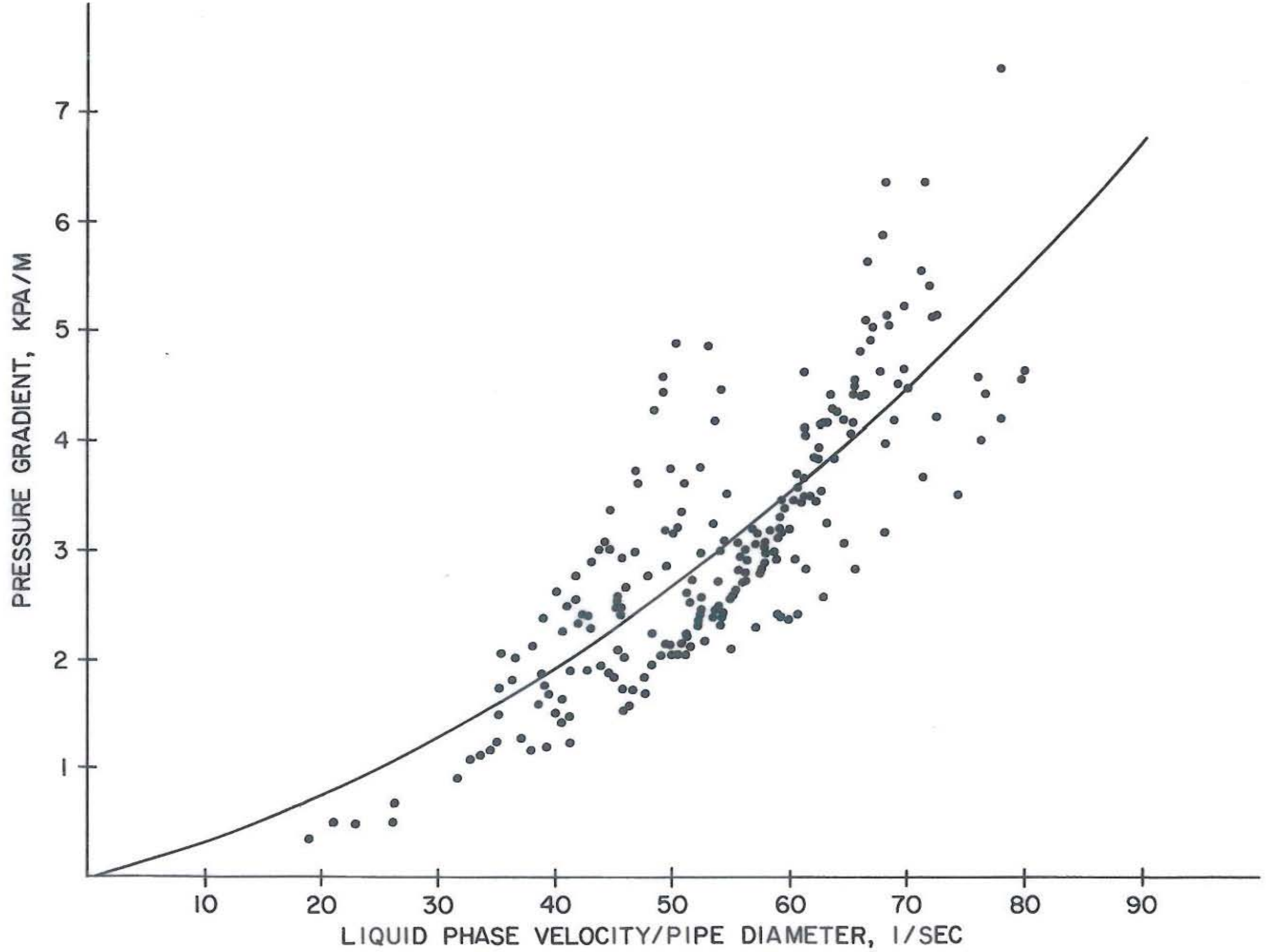

Fig. 3.5: Measured straight pipe pressure gradient versus V_L/D for all runs

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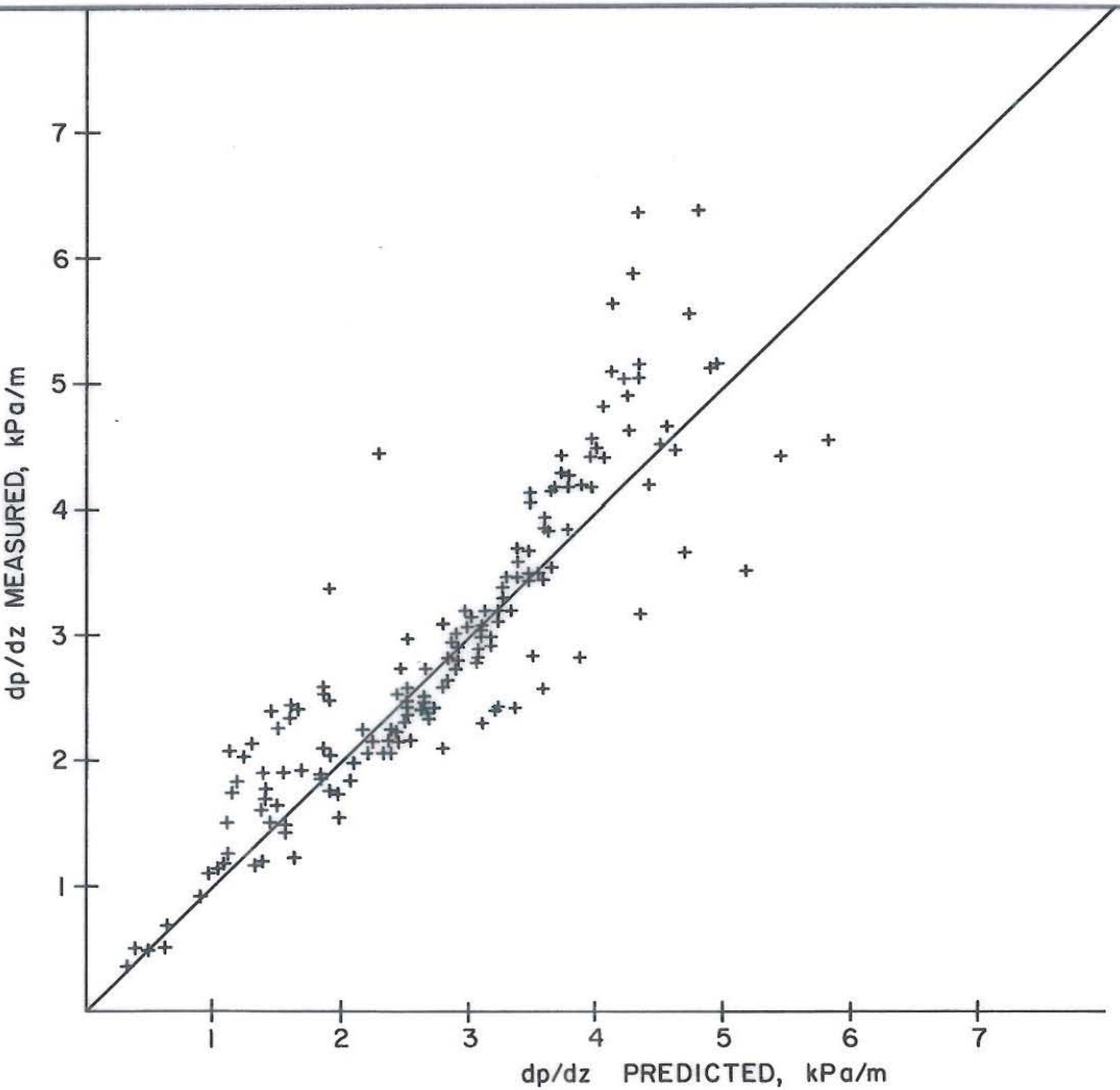

Fig. 3.6: Measured pressure gradient versus pressure gradient predicted by

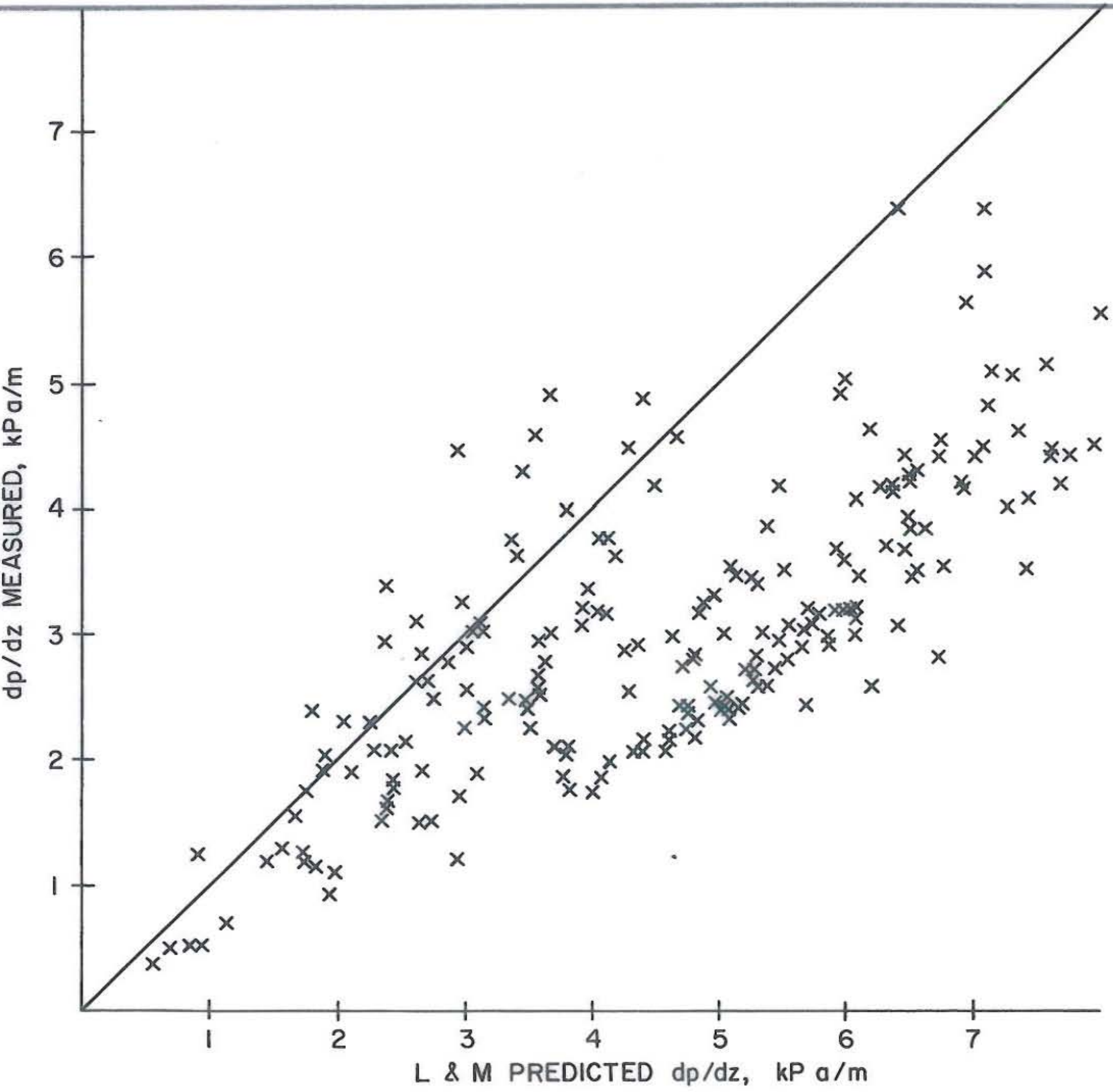

Fig. 3.7: Measured pressure gradient versus pressure gradient predicted by

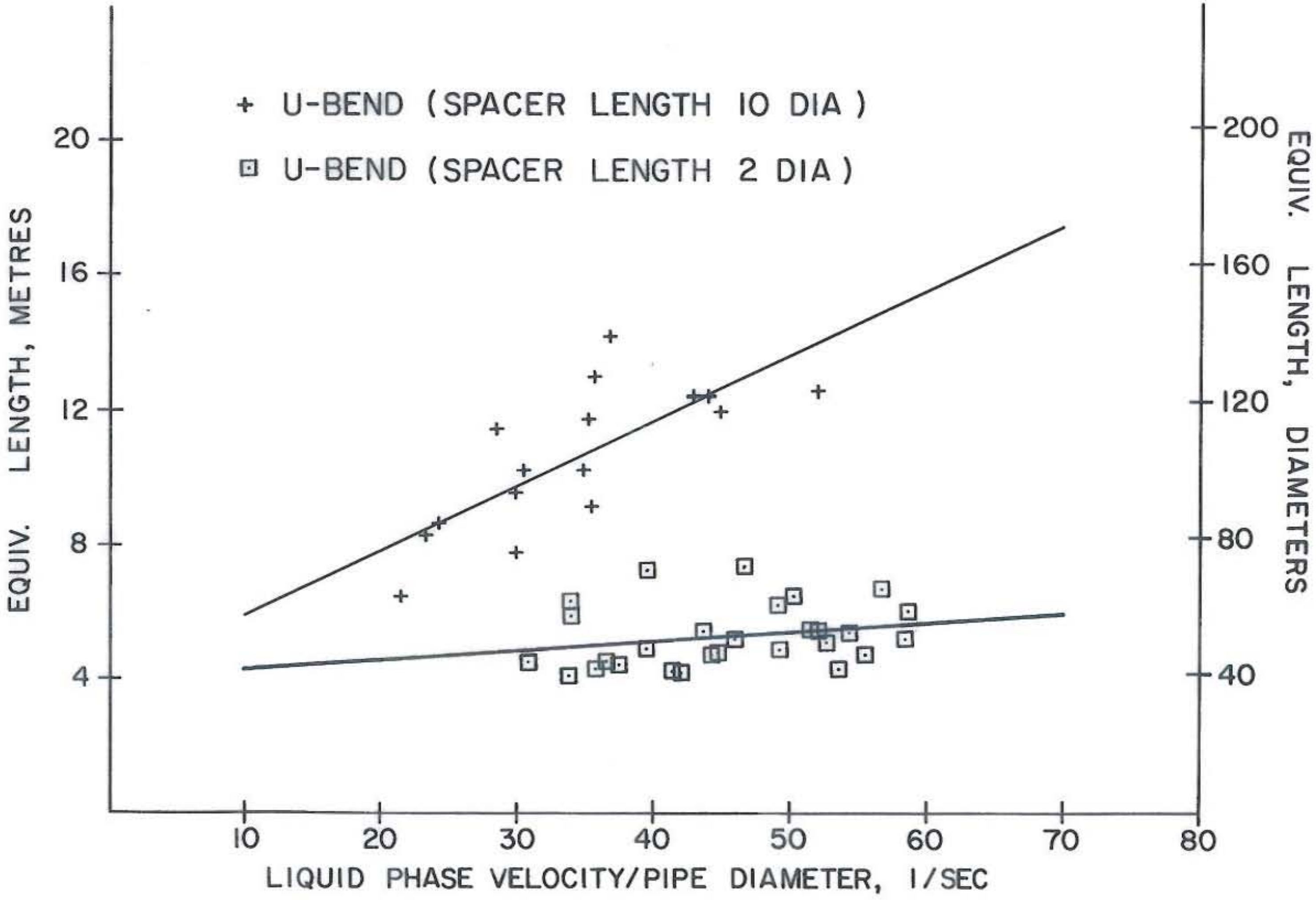

Fig. 3.8: Equivalent length of straight pipe versus V_L/D for U-bend

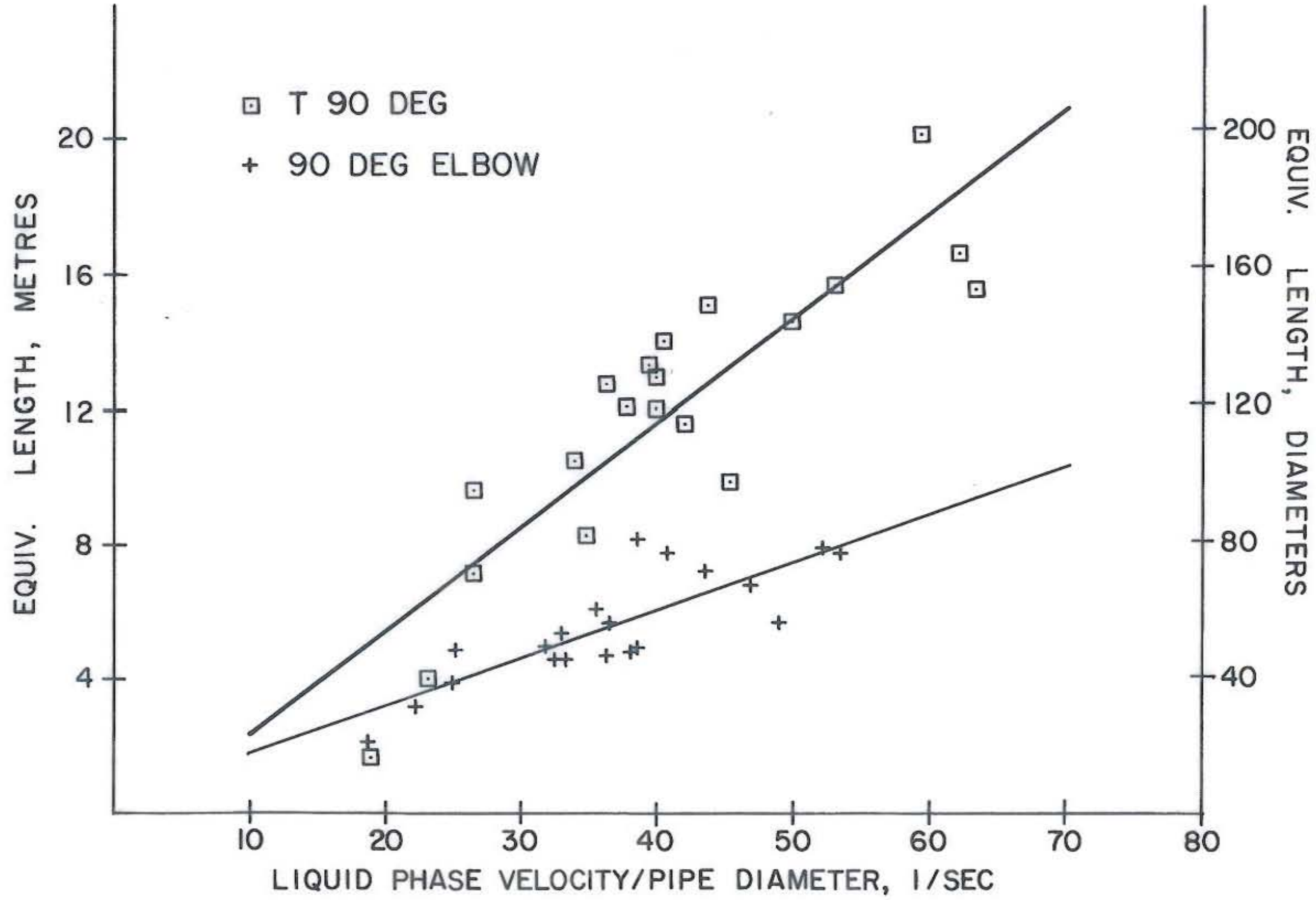

Fig. 3.9: Equivalent length of straight pipe versus V_L/D 90° elbow and T 90° sharp bend

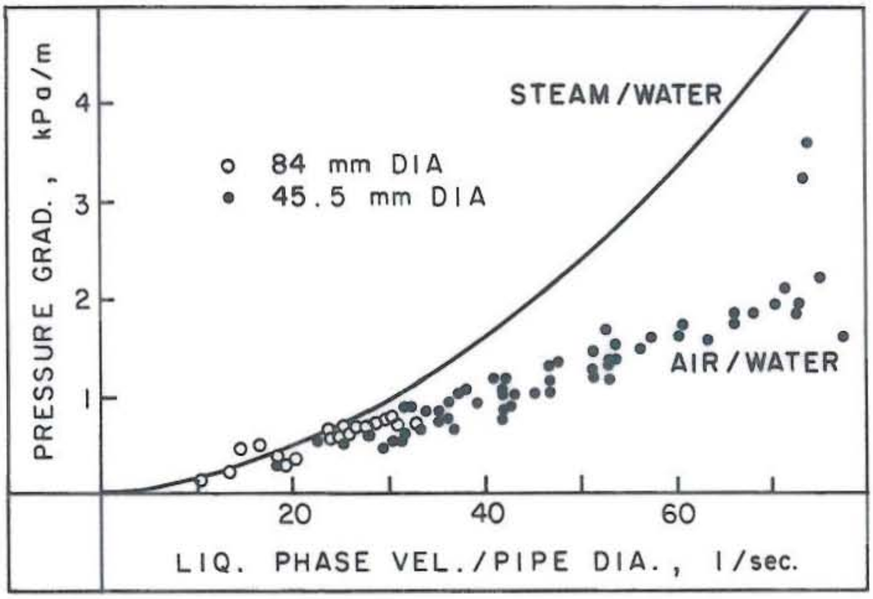

Fig. 3.10: Comparison of steam/water and air/water pressure gradient

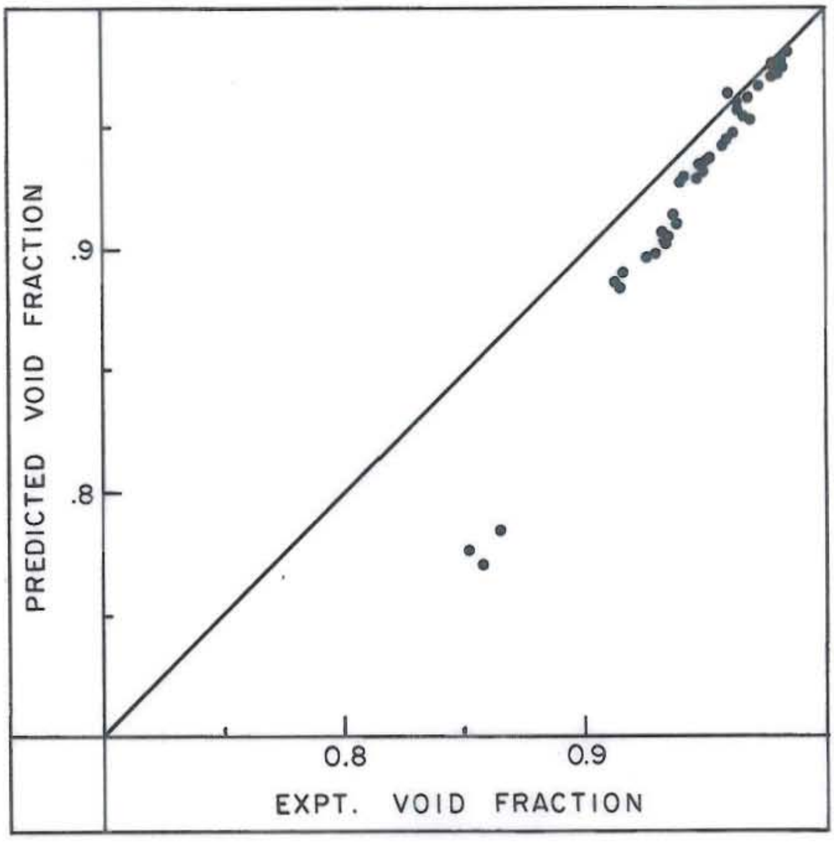

Fig. 3.11: Comparison of predicted and experimental void fraction - air/water experiment

4. TWO PHASE INCLINED FLOW, BOREHOLE PRESSURE DROP ESTIMATION AND CONDENSATION POT DESIGN

4.1 Inclined Flow

Work on the 10 cm loop included tests for upward flow in an inclined pipe. Pipe inclinations of 21°, 44°, 66° and 90° were possible. The flow down the inclined pipe could be resolved by a lip pressure gauge on the discharge end and during these tests use was also made of the tee to obtain pressure drop information for dividing flows.

4.1.1 Inclined Pipe Loss

The gravity component as stated earlier in Lecture 3 is given by

$$\frac{dp}{dz}_g = \bar{\rho} \sin \theta$$

and the mean mixture density

$$\bar{\rho} = \frac{\rho_L}{1 + Y/_{VR}} + \frac{\rho_G}{1 + VR_{/Y}}$$

where $Y = \beta_{/(1 - \beta)} = \frac{x}{1 - x} \cdot \frac{\rho_L}{\rho_G}$

For homogeneous flow VR = 1 and

$$\bar{\rho} = \rho_G \beta + \rho_L (1 - \beta)$$

or, in terms of x

$$\frac{1}{\rho_G} + \frac{1 - x}{\rho_L}$$

and for separated flow

$$\bar{\rho} = \alpha\rho_G + (1 - \alpha)\rho_L$$

The correlation of Premoli et al (1970) for vertical flow modified by Beggs (1973) orientation factor was chosen, as the authors claimed to account for inclined pipe losses. The Premoli et al (1970) uses the velocity ratio rather than void fraction. The two are related by

$$\alpha = 1/(1 + \frac{VR}{Y})$$

After determining the velocity ratio from the Premoli et al (1970) correlation, it is converted to a void fraction for the vertical pipe case. Using the homogeneous mixture velocity, a Froude Number is calculated, and a liquid velocity number. These enable a flow regime (one of three) to be selected which, from the appropriate Beggs (1973) equation, allows first a flow regime factor then a further coefficient which depends on the direction of flow, i.e. up or down flow, to be estimated. Finally, the void fraction from the Premoli et al (1970) correlation is factored by an equation involving these numbers. The calculation technique is detailed in ESDU Item 77016 (1977).

4.1.2 Inclined Pipe Tests

No satisfactory method of accounting for inclined pipe losses has resulted so far from this work. The experimental data has been compared with two correlations. Figure 4.1 presents the measured results compared to the methods of Premoli et al (1970) and Beggs. The gravity component was obtained by subtracting the horizontal straight pipe friction loss from the measured quantities, also making an allowance for the acceleration component. It is seen that the prediction is well below that of the one measured. It would appear, however, that the technique might be suitable for much smaller angles than 20 degrees and for small mass velocities.

If instead of using the velocity ratio preditction, the Harrison void fraction is used then the result is as Figure 4.2. Again, the correlation is not good although for angles up to about 40 degrees there is a reasonable fit to the data. This method cannot be expected to give a good result since the data base for determining the void fraction relationship is based on measurements in a horizontal pipe with predominantly annular flow, and as was stated earlier for incline flow, patterns change and the pressure drop correlation becomes out of range.

From this work it is clear that pressure drop is a fraction of flow regime. Spedding and Chen (1980) have carried out extensive tests on an air water rig, in which they were able to measure hold up. Some of their results are presented in figures 4.3 and 4.4. The coordinates are frictional velocity U^{x} defined as (shear stress/liquid density)$^{1/2}$ and V_T,+ total velocity of phases. With these coordinates the resulting curves show a logical progression with V_{LS} the superficial liquid velocity. It is difficult from these curves to isolate one particular set of data in terms of the variables, however they do serve to show that inclined pipe loss is very much a function of angle which determines the flow regimes, the liquid superficial velocity for some flows having little significance. Upward and downward flows are covered in what is a very extensive set of measurements.

4.2. Geothermal Well-Pressure Drop Prediction.

4.2.1 Introduction.

The capability of accurately predicting flowing pressures in geothermal well producing steam-water mixture under various operating conditions has a wide application.

a) May be the most important for a developed field would be to combine this knowledge of wellbore behaviour with a reservoir simulation programme. This would provide a general fluid simulator for a geothermal field, and would allow complete modelling of the reservoir and the production system in a single pass. Its principial profit would probably be to predict the long-range performance of the reservoir, and determine in advance what its performance would be when it became partially depleted.

b) The optimisation of wellbore design for future wells in a partially developed field can be achived by calculating production rates for different casing diameters at a given wellhead pressure, and comparing the benefit of increased flow rates against the higher cost of larger diameter wells.

c) Calculations can be made to estimate the depthat which the precipitation of calcium carbonate scale is likely to occur for different diameters and mass flow rates. This is possible since the precipitation process is related to the pressure and temperature conditions in the wellbore. Then, the selection of operating conditions can be guided to cause scaling at shallower depths, making it easier to carry out clean-up operations.

d) An additional application would be the determination of procedures for starting up and testing wells. As the gas-lift is a common method for this purpose, the gas volume, pressure, and injection depth requirements can be determined if the pressure profile in the wellbore is known.

At the present time, most of the experience gained in vertical two phase flow has been inspired by the petroleum industry, nuclear reactors and air-liquid systems. Accordingly, it is not known yet in a definitive way which, if any, of the pressure drop correlations developed for these systems, is suitable for geothermal wells.

There have been a few critical reviews, Gould (1974), Upadhyay et al (1977),Denver (1978) with this objective. However, due to the difficulty in accumulating a substantial number of pressure data in geothermal wells for comparison, the results are limited in the range of well conditions studied.

The flowing fluid may enter the well as a single phase fluid steam or water, or as a mixture of both phases, the latter two cases being the most common in geothermal wells. And even for the liquid phase case, a steam-water mixture is very likely to occur in some portion of the well.

As water flows up the well, the pressure falls because of the reduced hydrostatic load imposed by the fluid column above, and friction in the wellbore. Finally, a point in the well is reached at which the local pressure is at the boiling pressure for the water temperature. At this point, flashing begins and some steam is formed. As more steam is formed, the fluid velocity increases augmenting the frictional forces and reducing the density of the overlying mixture.

Bubble, Slug, Transition and Annular mist may all be found in the bore, particular for high flow rate cases, however for lower flow rate wells the slug flow regime appears to be the most consistent.

Gould, (1974) applied four methods to calculate the pressure profile in some geothermal wells at Broadlands and Wairakei, New Zealand. He reported the method of Hagedorn and Brown (1965) as the best for slug flow compared with Orkiszewski (1967) and Aziz. The Turner-Ros correlation was used for annular mist and the Griffith and Wallis (1961) for bubble flow exclusively.

Recent work done by Upadhyay et al (1977) in geothermal wells from United States and Phillippines, used again Hagedorn and Brown, and Orkiszewski correlations together with the Beggs and Brill approach which was developed for inclined pipes. In this comparison, a review of this subject has been prepared by the Denver Research Institute (1978). A handbook in Geothermal Well Design is presented giving a series of graphs and a relatively easy procedure to estimate the well head conditions from the well bore bottom data, for different values of mass flow rate, production temperature and well bore diameter. The handbook is limited for wells being fed by liquid single-phase only and it is expected its major use will be in making an economic analysis to determining the feasibility of geothermal energy projects.

For this handbook, several of the more prominent correlations for two phase flow were considered. The selected method was a combination of the elevation pressure drop predicted by Hughmark's (1962) method, and the prediction of Duckler et al (1964) Case II for frictional pressure drop.

4.2.2 Selection of methods

The review suggests that the three methods should be tested for geothermal wells.

1. Hagedorn and Brown correlation
2. Orkiszewski method
3. Hughmark-Duckler method

These three correlations have been tested against others for vertical flows and are worthy of application to well bore design.

Two more methods have recently been developed (1975) and have been added to this study.

4. Hughmark-Wisman combination
5. Harrison correlation

Although these methods were not obtained specifically for geothermal wells, they have been tested for steam-water mixtures.

The Wisman (1975) correlation was developed for frictional pressure drop only in an analytical way and reported an improvement of about 10% when compared against Duckler method for experimental steam-water vertical flow, with diameters from 0.025 to 0.1143 m (1 - 4 inches).

For this work, the method is combined with the holdup predicted by Hughmark.

Finally, the Harrison (1977) prediction was developed primarily for horizontal geothermal pipelines which have bigger diameters than those used in previous correlations however it was demonstrated by Harrison (1977) to give acceptable results in vertical pipelines. A detailed description of these methods is given in Marquez (1980).

4.2.3 Source of data for comparison

In order to test the chosen pressure drop correlations, a selection of 5 geothermal wells from different fields is investigated.

BR-12	From Broadlands geothermal field, New Zealand
KA-27	From Kawerau geothermal field, New Zealand
M-102	From Cerro Prieto geothermal field, Mexico
OKY-6	From Southern Negros geothermal field, Philippines
WK-72	From Wairakei geothermal field, New Zealand.

4.2.4 Assumptions

Two principal assumptions were established to facilitate the general sequence for calculating the predicted pressure drop.
1) Adiabatic flow: - Assuming no heat transfer from the fluid to the surroundings, the steam quality can be calculated. Gould (1974) analysed wells from NZ giving flow rates 10·47 kg/s to 76·93 kg/s and concluding that heat transfer had little effect.

2) Pure steam-water mixture: - The effect of the total dissolved solids upon the water properties is neglected as well as the gas effect in the steam phase. This is expected to be acceptable for the contents of the wells investigated here. However, the wells M-102 and BR-27 could be analysed in greater detail taking account of the water concentration of M-102 which is around 2% (20,000 ppm) at reservoir conditions, and the gas content of BR-27. A gas flow rate of 0.28 kg/s is reported for this well whose mixture production is 10.56 kg/s.

4.2.5 Procedure of calculation

The sequence of the principal steps for determining the predicted pressure drop along the well is summarised as follows:

a) Starting with the well head fluid conditions, a small pressure increment ΔP_T is selected.

b) Using the average pressure over the increment, the water and steam properties are obtained considering phase equilibrium.

c) A new steam quality is computed

d) Using the selected correlation, the terms ΔP_a , τ_f and P_m are calculated and the length ΔZ in which the specified ΔP_T occurs, is determined

e) The pressure is increased again by an increment and the corresponding ΔZ is calculated following the steps b, c and d.

f) This procedure is continued until the total depth of the well is reached or when the change of phase occurs.

Notes:-

1. In wells where the well head pressure is recorded by different gauge to that used for the pressure survey, the starting point was considered at the first 100 m depth in order to avoid any difference between the readings of the instruments.

2. The increments ΔP_T selected along the well were not constant but always conserved within 10% of the preceding pressure.

3. When a change in diameter of the well was found during the calculations, the point where it occurred was considered as a new starting point.

4. The values of roughness used in this work were those proposed by Gould (1974)

$\epsilon = 4.57 \times 10^{-5}$ m. (0.0018 inches) for the casing.
$\epsilon = 13.72 \times 10^{-5}$ m. (0.0054 inches) for the liner.

The shear stress (τ_f), the mean density ρ m and the acceleration term ΔP_a are determined as a function of hold up dependent upon the prediction method adopted.

4.2.6 Results

To give an idea of the well and flow conditions analysed, a summary with the range of the principal parameters are presented.

Well diameter	(D)	0.147 - 0.290	m
Well depth with two phase flow	(Z_{TP})	600 - 1500	m
Mass flow rate	(M_T)	10.56 - 60.83	kg/s
Bottom enthalpy	(h_B)	1171 - 1522	kJ/kg
Well head pressure	(P_{WH})	11.9 - 73.8	Bars
Pressure at the flash point	(P_{FP})	20 - 128	Bars
Steam fraction	(X)	0 - 0.28	-
Surface water velocity	(V_{SL})	0.036 - 2.46	m/s
Surface steam velocity	(V_{SG})	0 - 33.3	m/s
Predicted flow regime	-	*Slug flow only	-

*The flow regime for each increment was predicted using the boundaries proposed by Orkiszweski (1967).

The slug flow appeared almost exclusively. Only the first part of 110 meters below the well head of WK-72 was predicted as transition flow regime but then it was close to the boundary of the slug flow regime.

Figs. 4.5 to 4.8 give a graphical evolution of the methods and Figs. 4.9 to 4.12 are examples of the predicted profiles compared to the observed.

4.3 Condensation Pots

4.3.1 Introduction

At Wairakei a water steam mixture is discharged from the well head to a separator from which the steam phase is piped by branch lines which convey the steam to the power house. The efficiency of the separators is very high; a dryness fraction of 99.97% has been measured (James 1975). However, there is still a significant carryover of water into the steam line. In addition, although the pipelines are insulated there is a heat loss which results in some water condensing from the steam phase. Recent tests at Wairakei indicate that the steam phase in the main transmission lines may be of the order of 0.5% wet.

The bore water contains dissolved chemicals. The chemical composition in the water within the separators at Wairakei is about 1500 ppm (parts per million), mostly chlorides, which must not be allowed to enter the turbine. To remove water from the pipelines due to these two causes, condensation extraction pots are located at intervals down the lines. James (1975) claims an efficiency of 70% for these pots and, with an assumed steam dryness of 99.97 and condensation within the pipeline due to heat loss of 0.1% of the steam flow between two extraction pots, he demonstrates that after the first two pots every subsequent two pots reduce the chemical concentration in the water by more than an order of magnitude (11.11). McDowell (1975) describes tests on a 280 mm diameter pipeline from Wairakei bore 216 in which over a pipe length of about 400 m including some loops and bends, with 5 drain pots the chlorides were reduced from 1640 ppm at the ball check valve to about 3 ppm after the 5th pot.

Early research on the design of the pots had indicated that the most effective drain pot depth was 3x diameter of the pipe to be drained. Any decrease in this depth caused turbulent re-entrainment prior to the working of the steam traps. Unfortunately the drain pots in the Wairakei bore field (except for alarm traps) vary in depth between 0.5 and 0.7 diameters. The dimensions were conditioned by, among other things, the clearance available between the pipeline and the ground.

In 1971, during the optimisation study of the Wairakei field and power plant, a new 1.22 m (48 in.) diameter ILP line was designed and it was considered necessary to look at the proposed catchpot design particularly with reference to its efficiency in removing condensate. In 1977, during the biennial shutdown of the Wairakei power station, corrosion/erosion damage in the two 76 cm (30 in.) diameter H.P. steam transmission lines was discovered, and, as part of the investigation programme, means of improving the efficiency of the catchpots was proposed, to reduce the condensate flow.

4.3.2 Flow in Cavities

The majority of the work on cavity type flows has been done on rectangular cutouts. Roshko (1955) measured the pressure and velocity fields along the centreline of a slot formed in the floor of a wind tunnel. The depth of the cavity could be varied between 0 and about 25 cms. The pressure on the centre of the floor of the cavity as a fraction of depth is shown in Figure 4.13. The pressure coefficient Cp is defined by Cp = (p.ref)/ $1/2\rho u^2$ where p is the local pressure, i.e. at position 14, and p.ref. is the static pressure at the reference position which is just upstream of the leading edge of the cavity, and u is the free stream velocity well outside the floor boundary layer. The features of this curve are a shallow cavity regime from a h/b up to about 0.1 where the pressure on the base of the cavity is positive and a deep cavity region where the pressure is negative. The maximum positive pressure coefficient of 0.18 occurs at a h/b = 0.06. Measurements with a flattened pitot tube facing upstream close to position 14 indicated that, soon after the maximum pressure is reached, separation of the flow in the cavity floor occurs. Between h/b = 0.5 to 0.87, and above h/b = 2, fluctuating pressures were measured with the change from intermittent to steady at h/b = 0.87 occurring quite sharply. Wool Tuft studies indicated that a single steady vortex is first formed in the cavity at this value of depth. These intermittencies, which create large pressure and velocity fluctuations, appeared to be due to switching back and forth between two stable states. They occur intermediate to those for which stable systems may exist.

Experimental work by Tani et al (1961) largely confirmed Roshko's work and added data showing the turbulence and shear stress variations in rectangular cavities as a function of h/b. He noted that these parameters (turbulence, shear stress) in the mixing region of the shallow cavity (h/b = 0.4) are stronger than for the square cavity (h/b = 1.0). The effect of upstream boundary layer characteristic does not seem to be significant in establishing the stable cavity flows.

Mills (1961) supplemented experiment with a theoretical analysis for a square cavity but one of the main features of this work was to establish the flow pattern in the cavity as a function of depth (fig. 4.14). This work shows a series of stable flow situations except for the range $0.25 < h/b < 0.80$ in which an unsteadiness occurs reaching a maximum at about h/b = 0.5-0.6. It is deduced that the unsteadiness is due to periodic fluctuations of the vortex in the vertical direction.

The effects of three dimensionality of the flow in rectangular cavities was investigated by Maull and East (1963) using a visualisation technique (oil flow) and surface static-pressure distributions. They demonstrated that the three dimensionality of the flow was a function of cavity depth.

During investigations of the flow and heat transfer characteristics of nuclear fuel elements, flow patterns over a range of depths were observed by Lewis (1966) in a rectangular cavity in a closed circuit water tunnel. Between depth/chord/ratio of 0.25 to 0.8 the spanwise variations described by Maull and East (1963) were largely observed. However, Lewis indicates that flow appeared to enter the cavity near the side wall, being largely contained in the trailing vortex filaments (Fig. 4.15).

For h/b = 0.8 to 1.25 a "W" vortex was formed - a sinusoidal vortex filament of two wavelengths, the plane of which rotated as a function of depth; it was vertical for a square cavity. Above h/b = 1.25 two alternate flow patterns were observed, generally mirror images of each other. The "W" vortex is thought to arise from end effects which, because of the small span/chord ratio (=2), would control the flow in the whole cavity.

4.3.3 Model Experimental Work

4.3.3.1 First Series

A pressure tapped cylindrical cavity (catchpot) (Figure 4.16) was mounted in an air rig (mean velocity 43 m/s) in a region of fully developed flow. The rig discharged to atmosphere, and conditions in the model line were considered to be typical of those experienced in the 1.22 m line at

Wairakei, i.e. high dynamic pressure compared to static pressure. Two types of tests were conducted ; first, pressure profiles were measured for a range of cavity depths, and secondly, known quantities of water were injected at the bottom of the pipe at two positions upstream of the cavity (9 and 69 diameters) and the collection efficiency of the catchpot estimated.

The pressure profiles both in the streamwise and normal directions were measured for a range of depths. Typical profiles are shown in Figure 4.17.

The pressure coefficient (Cp) profiles both in the streamwise and normal directions were measured. The magnitude and distribution of pressures was a function of depth. In general, for shallow depths the pressure on the upstream wall was negative leading to a negative pressure on the base, which rises sharply from a maximum suction on the base to a peak positive pressure on the downstream wall at the bottom of the cavity. The pressure then falls up the downstream face of the cavity. Above an h/d greater than 0.5 the pressure on the upstream wall is first negative, reaching a peak suction about half way down the wall before turning up at the upstream corner. There is a positive pressure across the base with a peak near the downstream wall. Finally there is a negative suction loop as the top of the cavity is reached.

The pressure coefficient at the centre tap on the base is shown as a function of h/d, at figure 4.18, and shows a clear suction peak at about h/d = 0.5. Tests were done at different airspeeds and indicate a small Reynolds number change; however the critical depth of about h/d = 0.5 was unaltered.

To obtain collection efficiency data - that is, the ratio of the amount collected to the amount flowing - a known quantity of water was injected (9 diameters or 69 diameters upstream of the cavity) at the bottom of the pipe. Figure 4.19 shows the variation of collection efficiency as a function of depth, and illustrates the effects of liquid to gas flow ratios. The method of injecting water into the bottom of the pipe was not entirely satisfactory but the results clearly show the influence of catchpot depth on the water retention.

The pressure profiles in Figure 4.17 appear to be of similar shape to those measured in two dimensional cavities. However, the instability experienced by Roshko was not evident here. Within the cavity the flow is complex and three dimensional. The pressure profiles and the water injection tests suggest for shallow cavities, i.e. $h/d < 0.5$, that the water deposited initially on the downstream wall is driven vertically down towards the base. The flow then splits and moves towards the side walls where a vigorous upward spiralling motion drives the droplets towards the lip, similar to that suggested by Lewis. In addition, particularly with the larger flows, a secondary loss occurs in which water is torn from the surface as it is forced towards the upstream wall of the cavity by the incoming airstream.

For cavity depths greater than $h/d = 0.5$, the pressure distributions on the walls and base suggest a more stable flow with a symmetry appearing in the profiles and the possibility of a stable vortex appearing. The retention of water improves with increasing depth. Water injected at 69 diameters upstream of the cavity is more typical of that in the full scale pipeline.

4.3.3.2 Second Series

As mentioned earlier, further tests were necessary as a result of a programme designed to alleviate the corrosion problem observed in the 76 cm (30 in.) diameter pipeline. The objective of these tests was to improve the collection efficiency of the pots.

The air/water rig of Lee (1978) was used for these tests. Air is supplied from a Roots blower via a flow measuring orifice to a 84 mm diameter perspex pipe arranged in the form of a 180° 'U' bend connecting two straight lengths 3 metres long. Water is injected through an annular injector which sprays the water on to the walls of the pipe at entry. A cyclone separator returns the water to the sump, the air being discharged to atmosphere. Water flow rate is measured by a calibrated rotameter.

A section was installed in the downstream tangent from the 180 degree bend, which included the test catchpot with an adjustable base and three other catchpots. These additional catchpots were used to collect water in the efficiency tests. This test position was chosen in order to utilize the bend to spread some water around the pipe wall, a condition which has been observed in the Wairakei pipes. The test catchpot was about 25 diameters downstream of the 'U' bend in a region which could be expected to have a reasonably well developed flow. A water outlet on the base of the test catchpot was included to empty the pot.

Two sizes of catchpot were tested, the dimensions chosen to correspond to a scaled model of those in use at Wairakei, the diameter of pipe (D) to diameter of catchpot (d) ratios being 1.5 and 1.0. Airflow was adjusted to give a pipe velocity of about 30 m/s, corresponding to the steam velocity in the 76 cm steam lines. A water flow rate was selected to give about the equivalent of 1% wetness. In these tests no attempt to model Reynolds number was made; the available apparatus did not permit correct Reynolds number scaling.

Following the tests of the basic catchpots, modifications were introduced. These are discussed later.

Pressure tappings on the top of the pipe and across the horizontal diameter were installed. These were sited one pipe diameter upstream and downstream of the pot, and pressure drop measurements taken on an inclined monometer.

Three techniques were used to estimate collection efficiency. Firstly, a deep catchpot > 2.0d was allowed to fill to a known depth and the discharge controlled to give a constant depth. Figure 4.20 summarises typical results from this type of test. Secondly, the plunger was set at a given depth and the catchpot discharge adjusted to give a constant depth of water equal to 0.125D over the base of the catchpot. A study of the results showed that at depths greater than about 0.5D the collection efficiency was virtually independent of depth.

The third technique used was to set the plunger base to a given depth, allow the water to build up to a fixed height, allow the water to build up to a fixed height. and discharge the water, allowing it to refill for the next cycle. This procedure was considered to be an approximation to the operation of the Wairakei drain pots. The results, although not covering the full range of plunger depths, showed the same trends as illustrated in Figure 4.20 ; that is, a peak collection efficiency for this diameter ratio ($\frac{D}{d}$ = 1.5) at about a h/d = 0.6 (h/D = 0.4) which is defined as the critical depth.

Visual observation of the flow into and around the catchpot largely supported the interpretation given in the earlier Series One tests.

It was noted with interest that below the critical depth the build-up of water in the catchpot was such that the air-water interface sloped in the direction of flow, i.e. the water was deeper on the upstream side. The drain exit, therefore, needs to be on the upstream half of the catchpot base. This was confirmed by the pressure distributions measured earlier.

The sensitivity of collection efficiency to variations in water flow was investigated. Below critical depth, no significant change in efficiency was detected for small changes in water flow. However, for h/d > 0.6 a 10% decrease in water flow, i.e. the air/water mixture becoming dryer, resulted in about a 7-10% improvement in collection efficiency. This was the result of less water spread on the pipe walls, more of the water flowing along the bottom of the pipe. Small increases in water flow did not show any measurable changes. It was not until the wetness had been increased from 1% to 4% that the collection efficiency reduced significantly.

The 76 cm (30 in.) diameter line at Wairakei has a number of drains which are 50 cm (20 in.) diameter and 20 cm (8 in.) deep (measured from the bottom of the pipe). These dimensions correspond to h/D = 0.27 (h/d = 0.4) which is below the critical depth and would be expected to have a low collection efficiency of about 60%. As discussed above, at this depth the flow inside the cavity is highly three dimensional and turbulent, but there is a tendency for water to move to the upstream side of the catchpot and to be re-entrained with the airstream. For this geometric design, attempts were made to improve the efficiency. To prevent the reversed flow, a baffle modelled in plasticine was placed transverse to the flow direction, fixed to the base and immersed within the cavity. Two different shapes were tried and both resulted in collection efficiencies over 95%. It was necessary, however, to ensure that there was a passage for the air within the cavity to traverse upstream. This was provided by small gaps around the edge of the baffle and in the centre. The most efficient baffle under all conditions was one in which the upper edge approximated to the pipe/catchpot intersection with 3 holes in the centre whilst a baffle which left the middle third of the diameter open performed satisfactorily.

Catchpot $(\frac{D}{d} = 1.0)$

A limited range of tests was carried out for a catchpot of $\frac{D}{d} = 1{\cdot}0$. The collection efficiency at three depths was measured. For 0.25D and 0.75D efficiencies were of the order of 90% whilst at 0.5D a very strong pair of vortices, rotating parallel to the flow on either side of the catchpot, was observed giving a collection efficiency of about 75%. Insertion of baffles, as described above, destroyed the vortex system and gave efficiencies over 95%.

The pressure drops across the catchpots are shown in Table 4.1 The pressure drop coefficient is expressed in terms of the dynamic head of the airflow.

TABLE 4.1

Catchpot	Mass ratio $^{air}/_{water}$ %	Pot depth $^{h}/_{D}$	$\frac{\Delta p}{1/2\rho \bar{u}^{2}}$
	1	0.27	0.013
$\frac{D}{d} = 1.5$	1.5	0.27	0.009
	4.4	0.27	0.010
$\frac{D}{d} = 1.0$	1	0.27	0.018
		0.52	0.131
	4.4	0.27	0.010
		0.52	0.025

Some recent full scale tests confirmed the basic results of these model baffle tests. Baffles were inserted into two drainpots in 'L' line at Wairakei (A 4/5, A5). The shape of the baffle is in Figure 4.21. The rate of condensate was measured and the results measured over a long period in Figure 4.22.

It is seen that on installation of the baffles the condensate discharge from the two drain pots rose from around 40 kg/hr to 140 kg/hr. It was estimated that this demonstrated an improvement in catchpot efficiency from about 40% to 95%. The performance at A4 was surprising and later traced to a blockage within the drain pipes.

From this work it is seen that drain pot performance is a function of depth and that shallow pots can be improved by installing a baffle plate.

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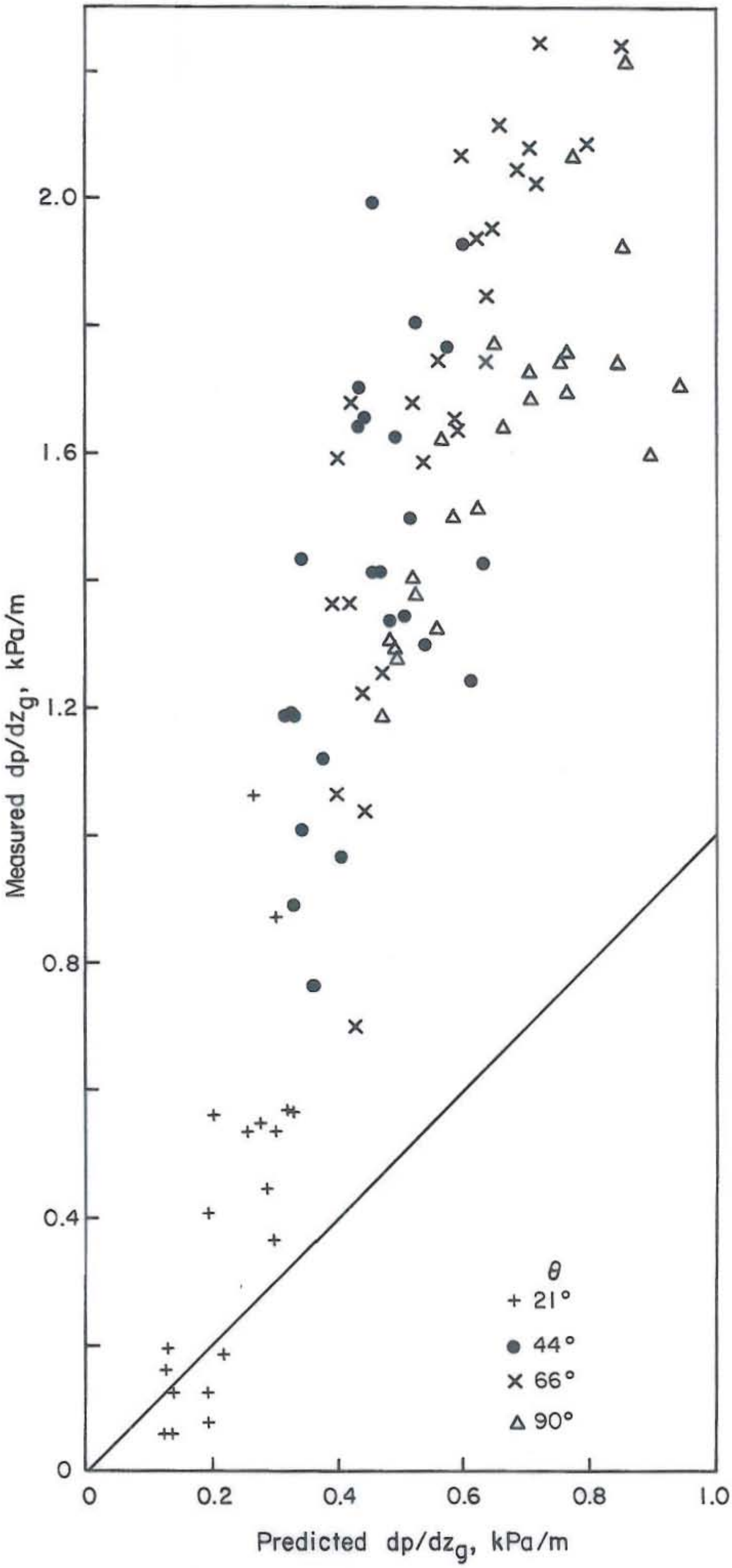


Fig. 4.1 : dp/dz$_g$ predicted by Premoli et al Correlation and Beggs Equation versus measured dp/dz$_g$.

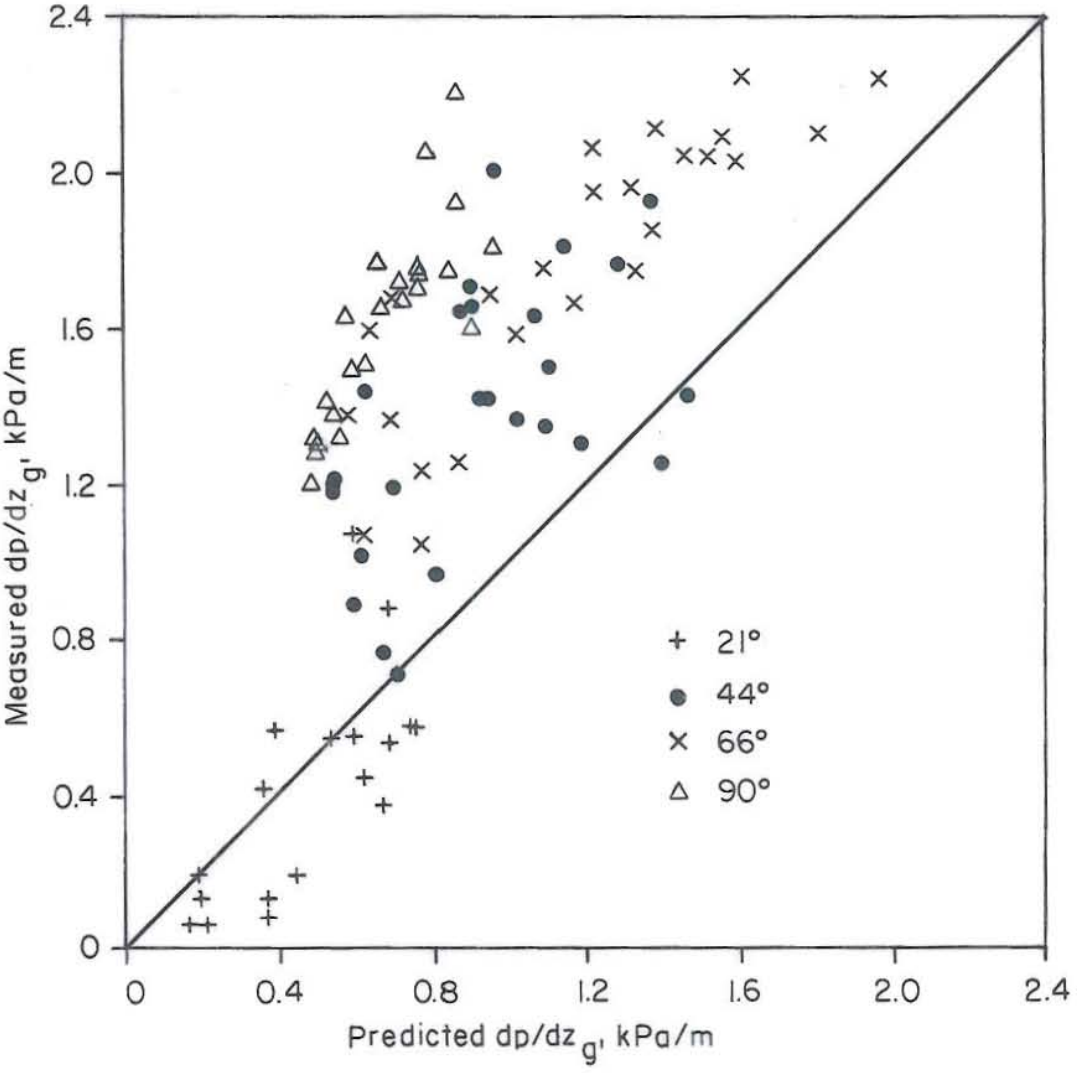


Fig. 4.2 : Gravitational component of pressure gradient in inclined pipe predicted by Premoli et al Correlation and Beggs Equations using void fractions predicted by Harrison Correlation versus measured gravitational component of pressure gradient.

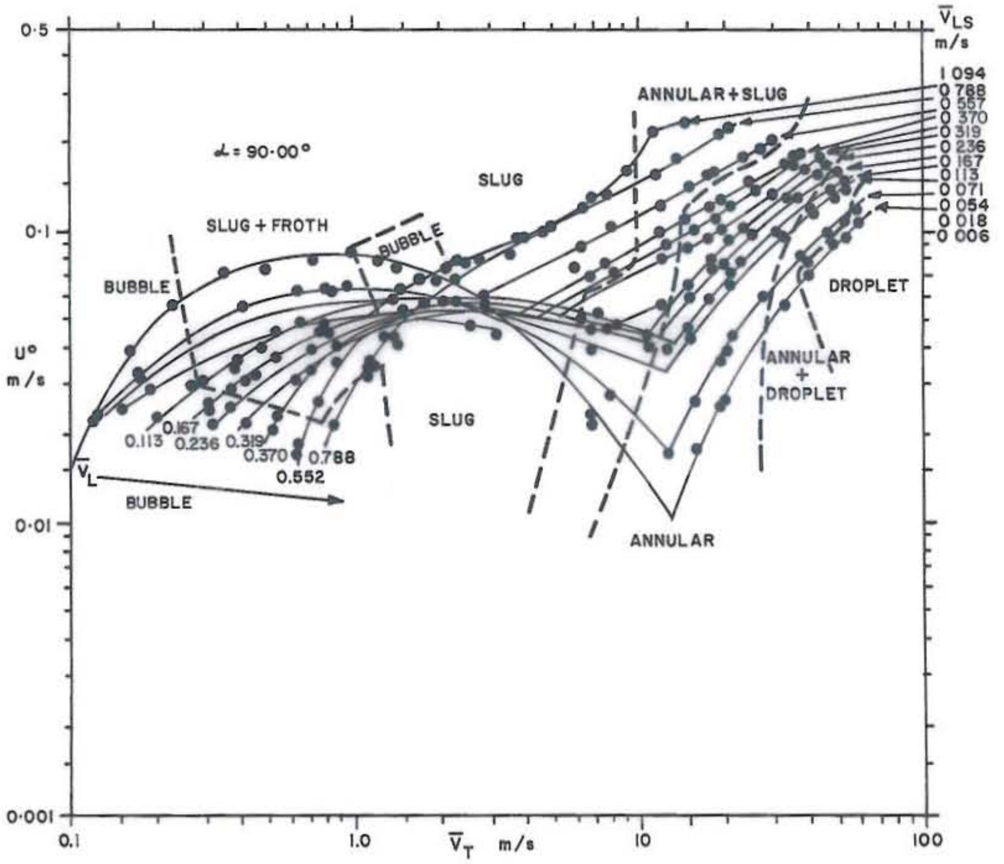


Fig. 4.3 : Frictional pressure loss for air-water two-phase co-current flow in a pipe at an angle of 90.00° from the horizontal (Spedding et al 1980)

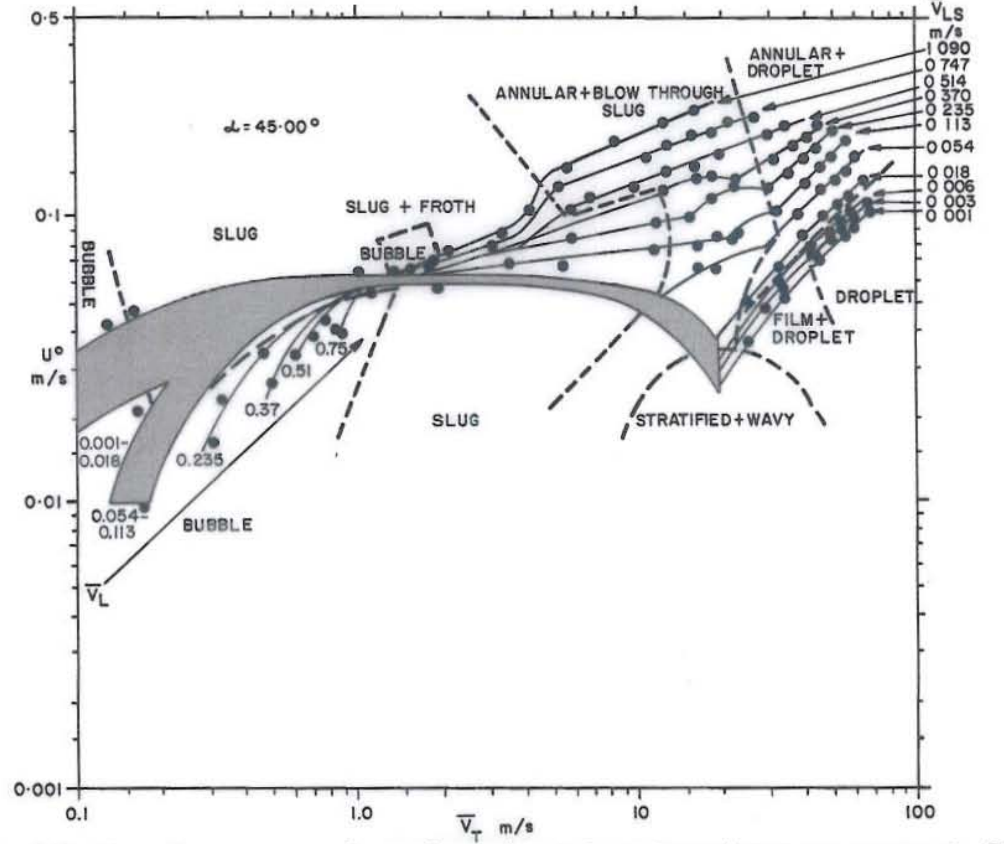


Fig. 4.4 : Frictional pressure loss for air-water two-phase co-current flow in a pipe at an angle of 45.00° from the horizontal (Spedding et al 1980)

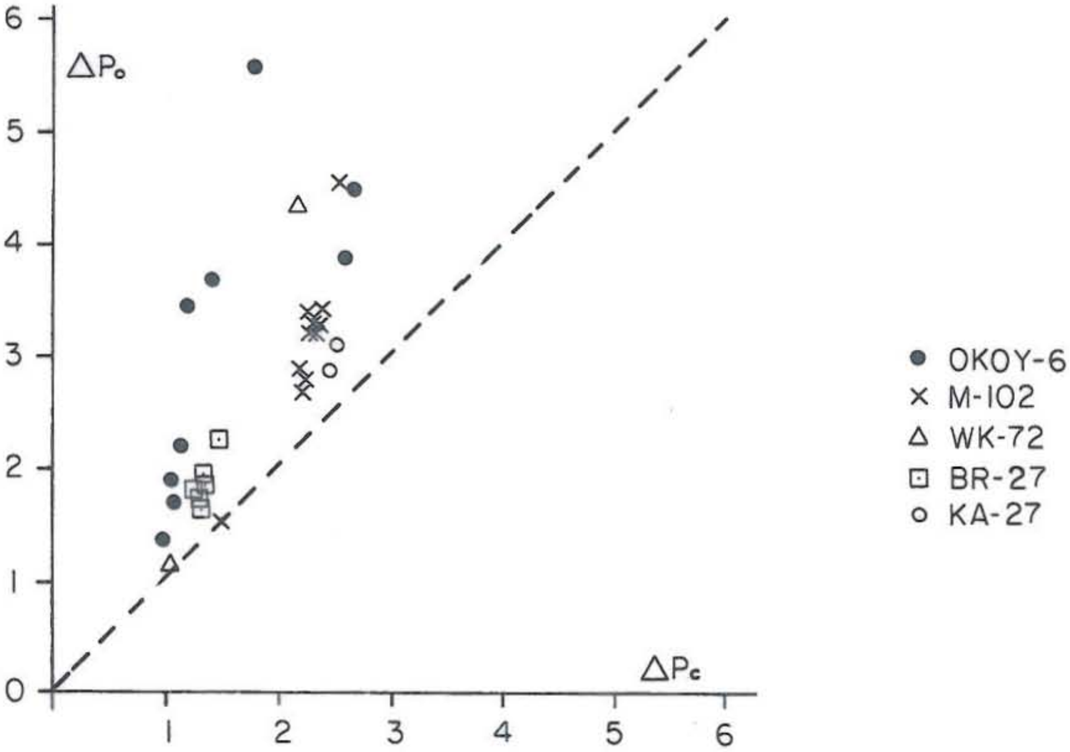


Fig. 4.5: Hagedorn and Brown Method (Marquez 1980)

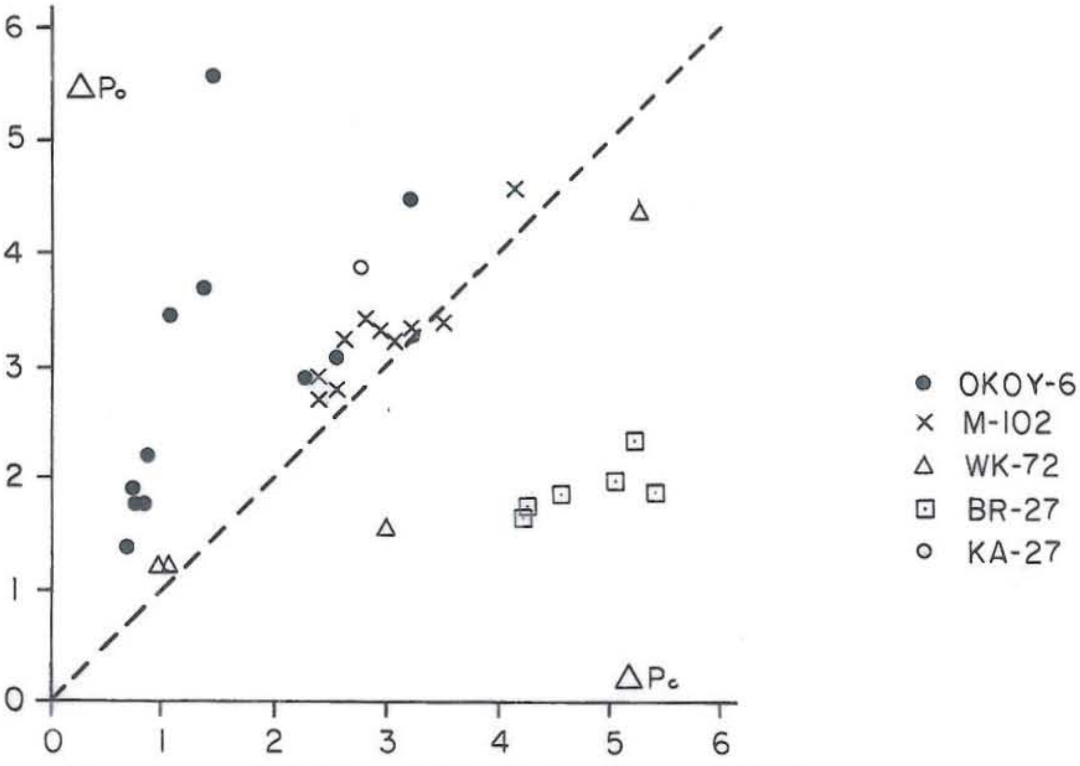


Fig. 4.6 : Orkiszewski Method (Marquez 1980)

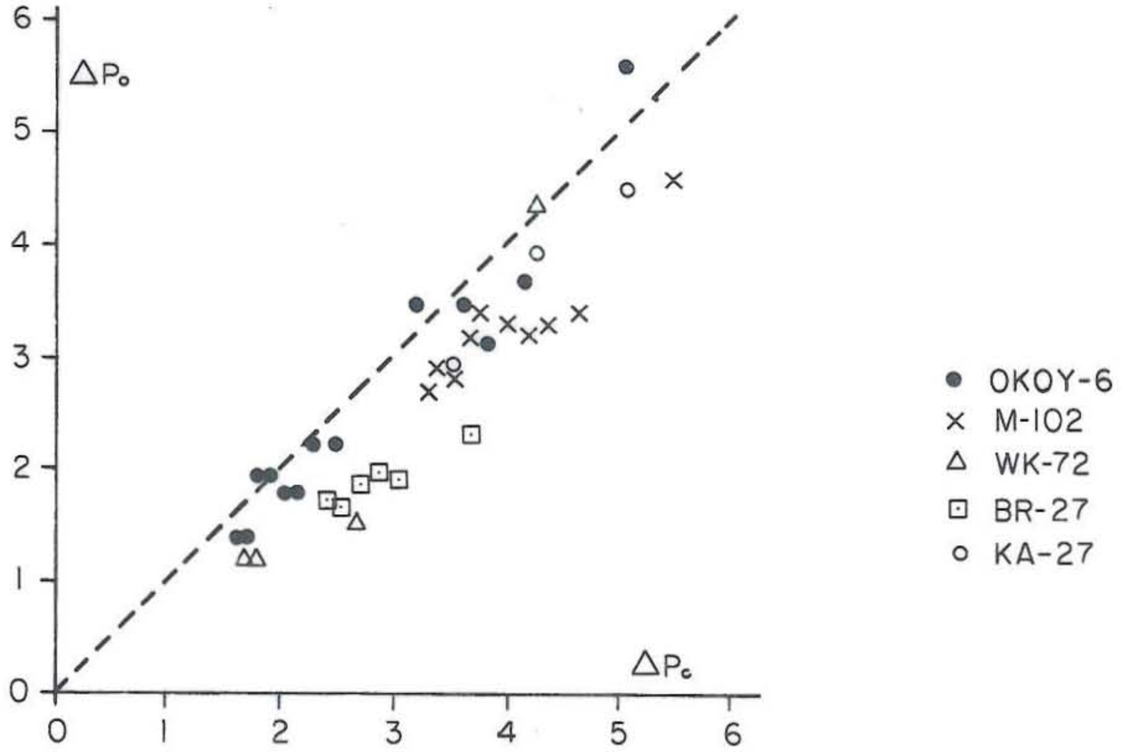


Fig. 4.7: Hughmark-Duckler Method (Marques 1980)

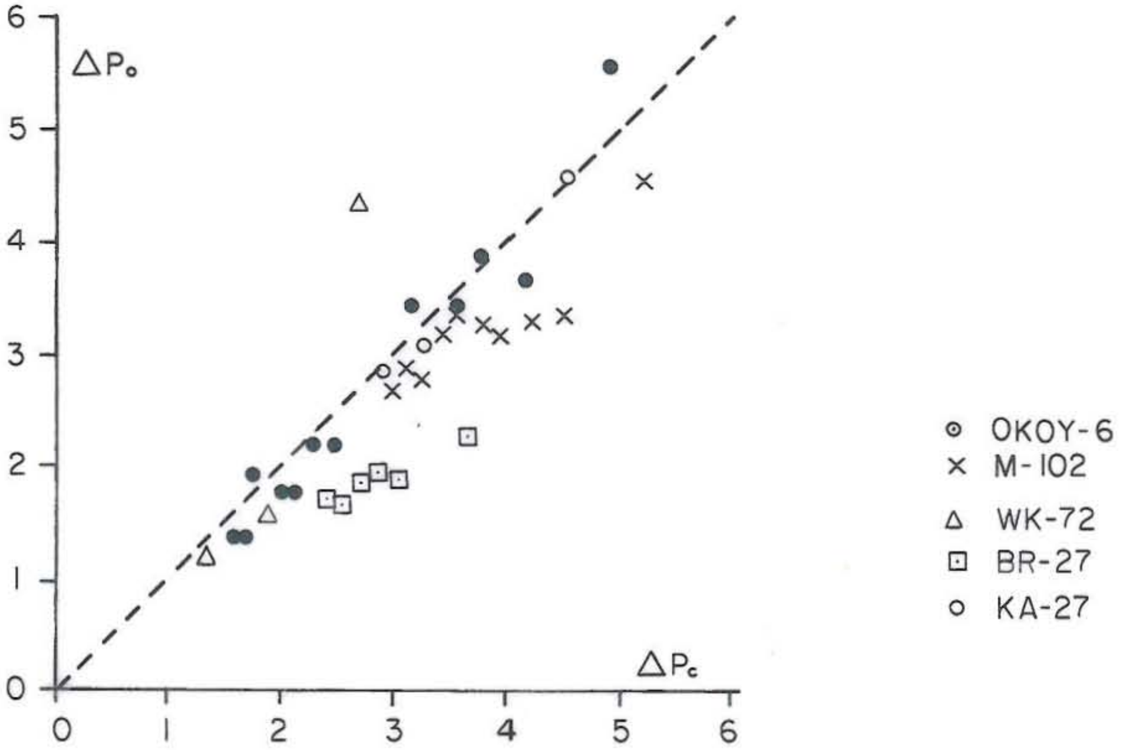


Fig. 4.8 : Hughmark-Wisman Method (Marquez 1980)

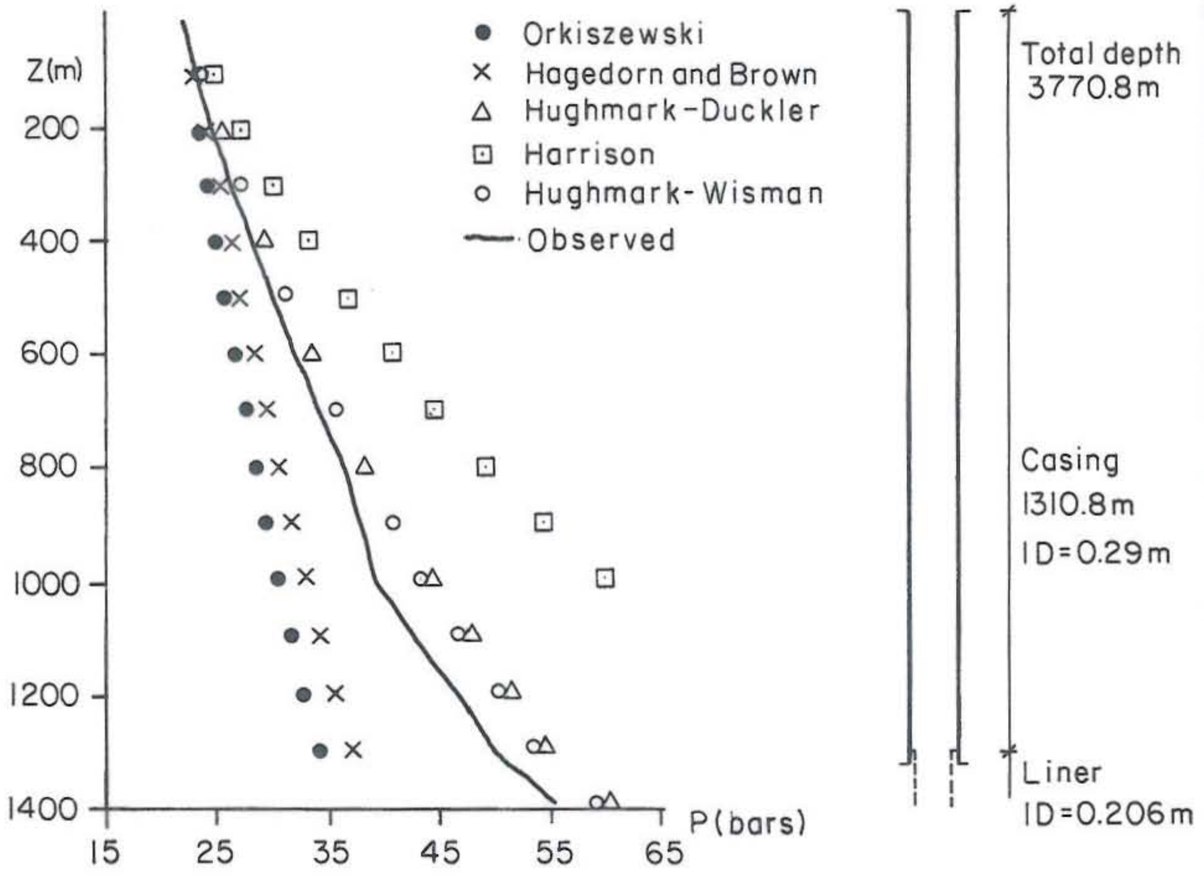


Fig. 4.9: Well OKOY-6: Pressure Depth Traverses

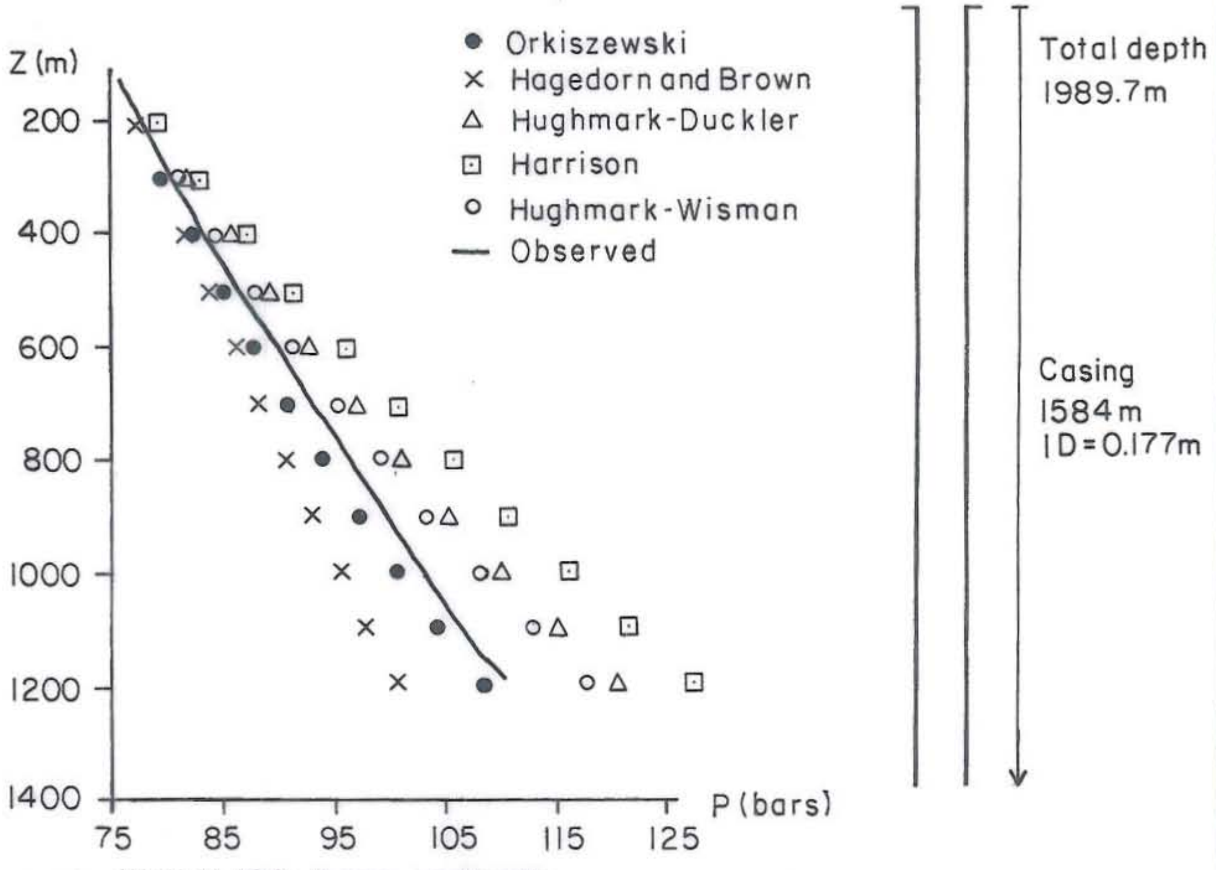


Fig. 4.10 : Well M-102: Pressure Depth (Marquez 1980)

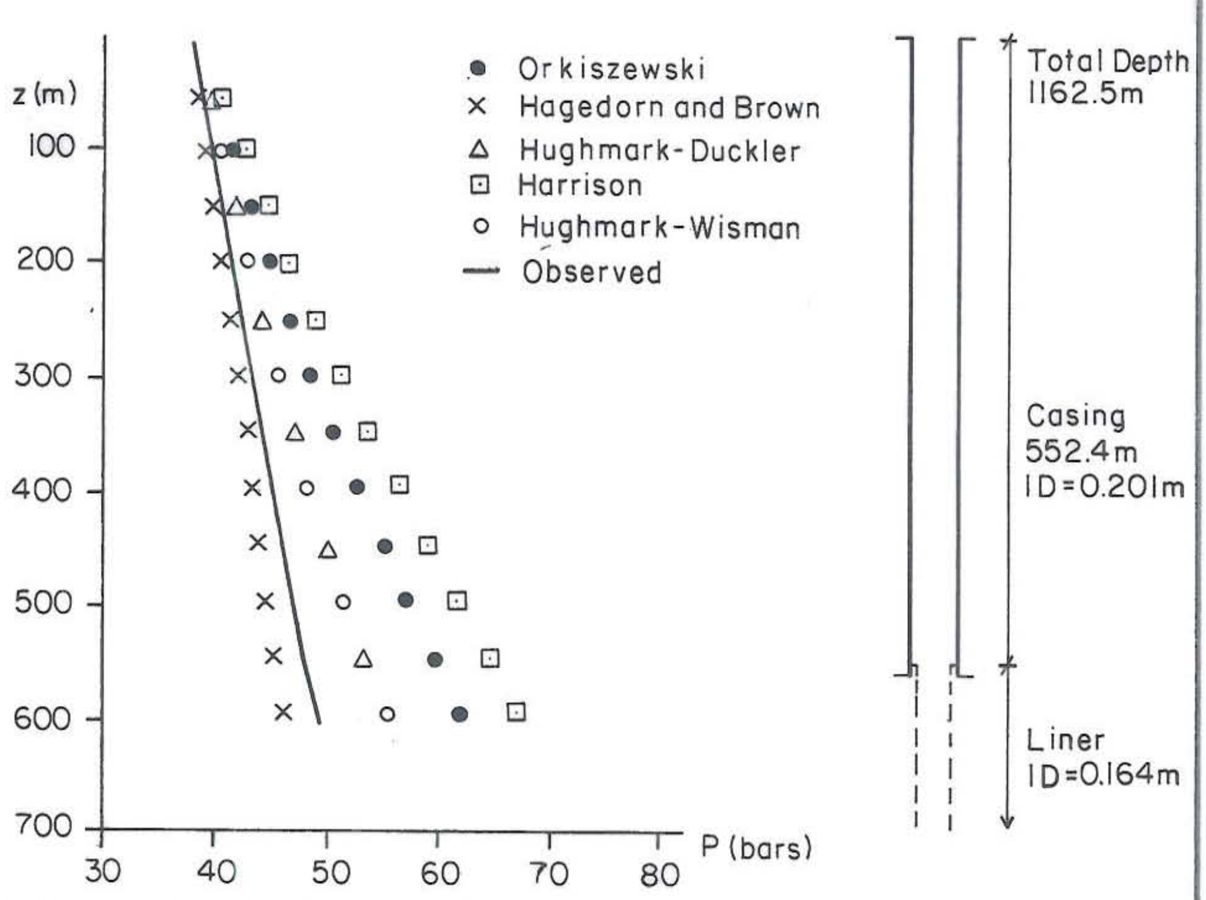


Fig. 4.11: Well BR-27: Pressure Depth Traverses

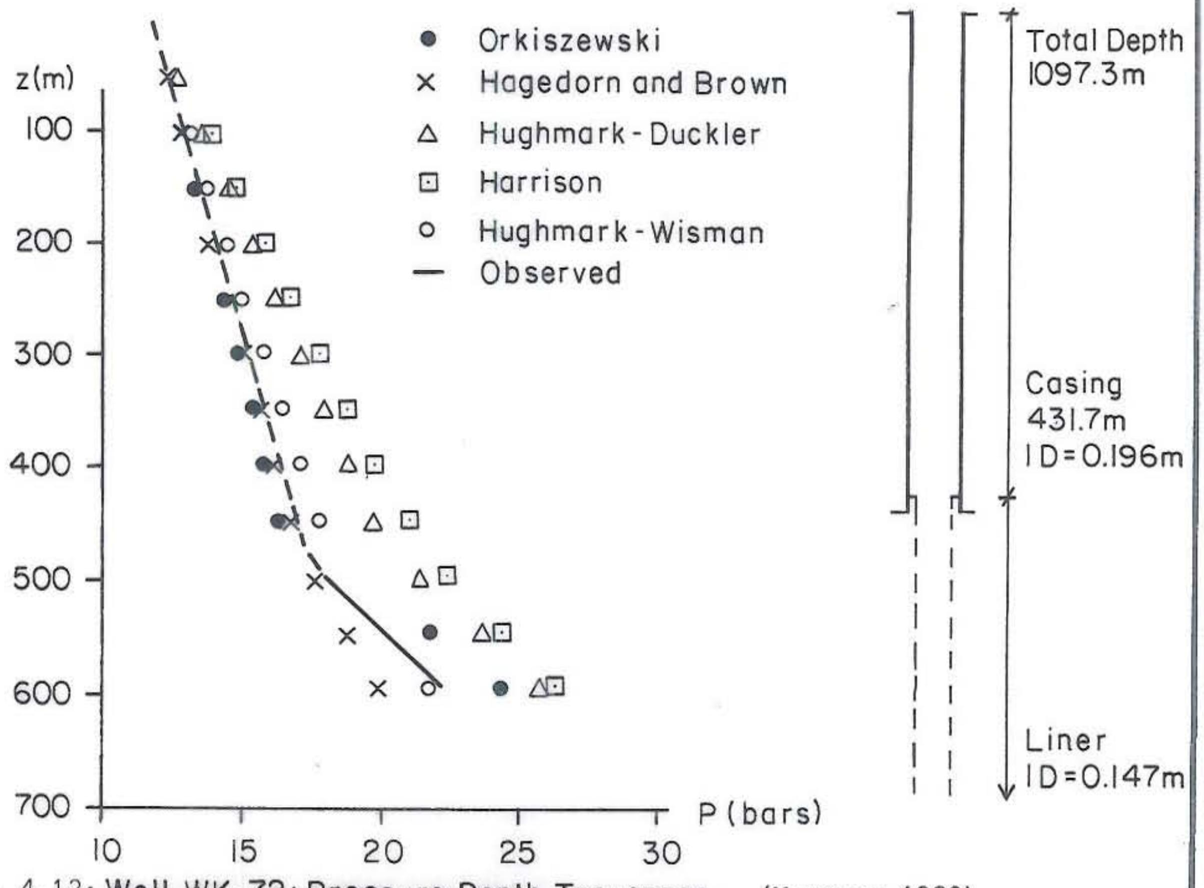


Fig. 4.12: Well WK-72: Pressure Depth Traverses (Marquez 1980)

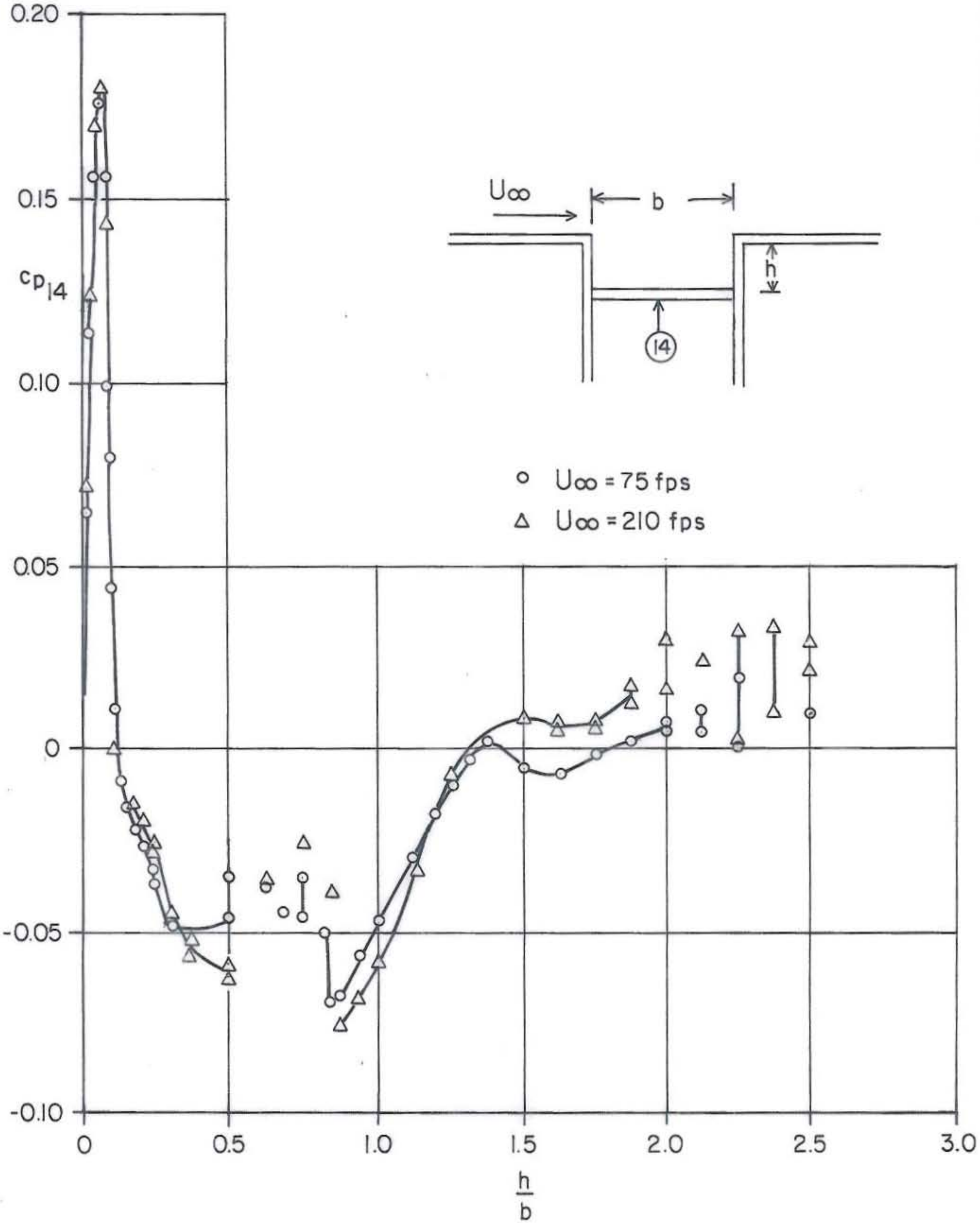
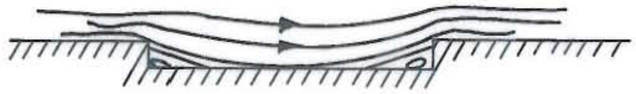


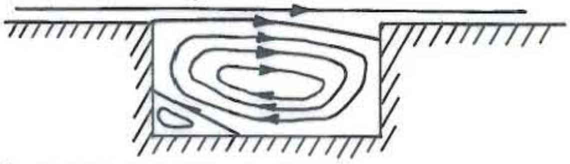
Fig. 4.13 : Relation of Shallow Cavity Regime to Deeper Cavities

(Roshko 1955)

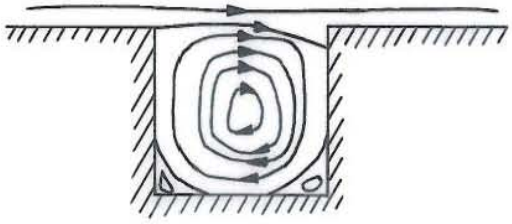


(a) $0 \leq h/b \leq 0.1$:-
Boundary layer flow and
corner eddies.

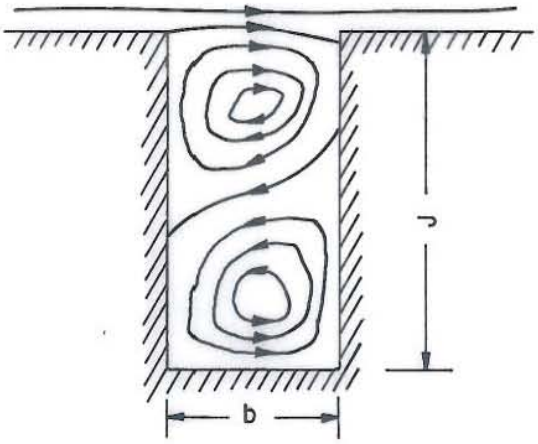
(b) $0.1 \leq h/b \leq 0.25$:-
Flat stable eddy and possible
small eddy.



(c) $0.25 \leq h/b \leq 0.80$:-
Unsteady main vortex and eddy.

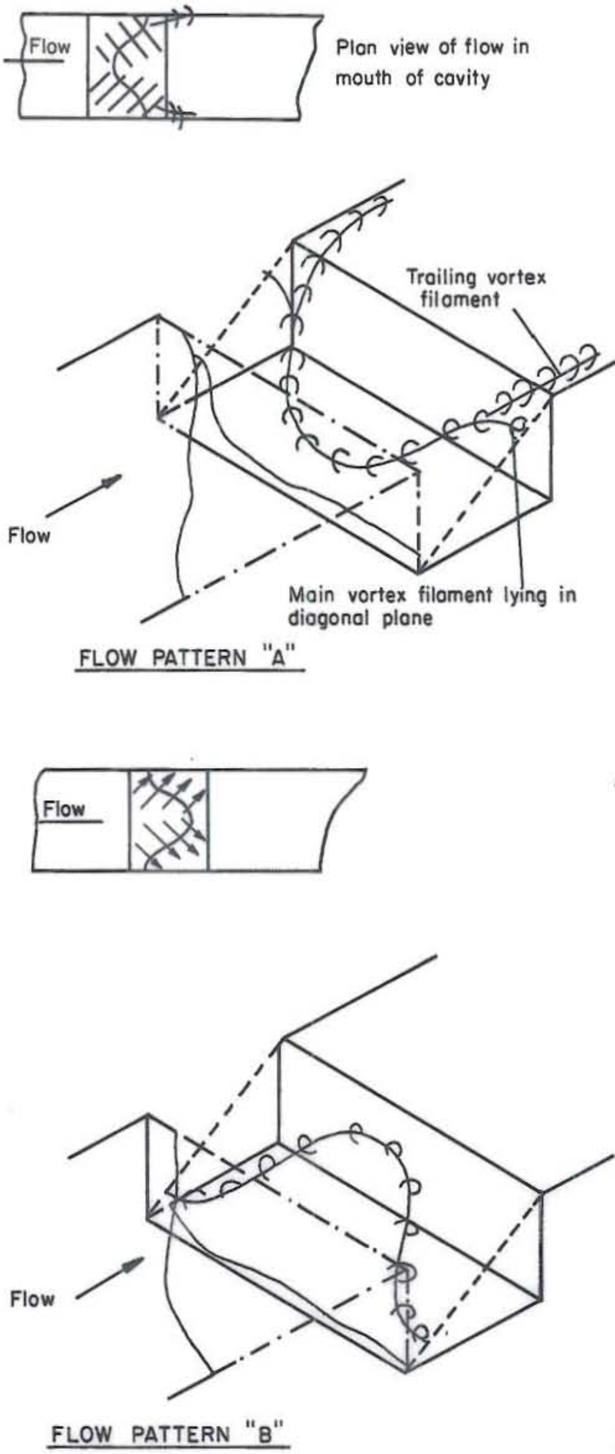


(d) $0.80 \leq h/b \leq 1.35$:-
Steady main vortex and eddies.

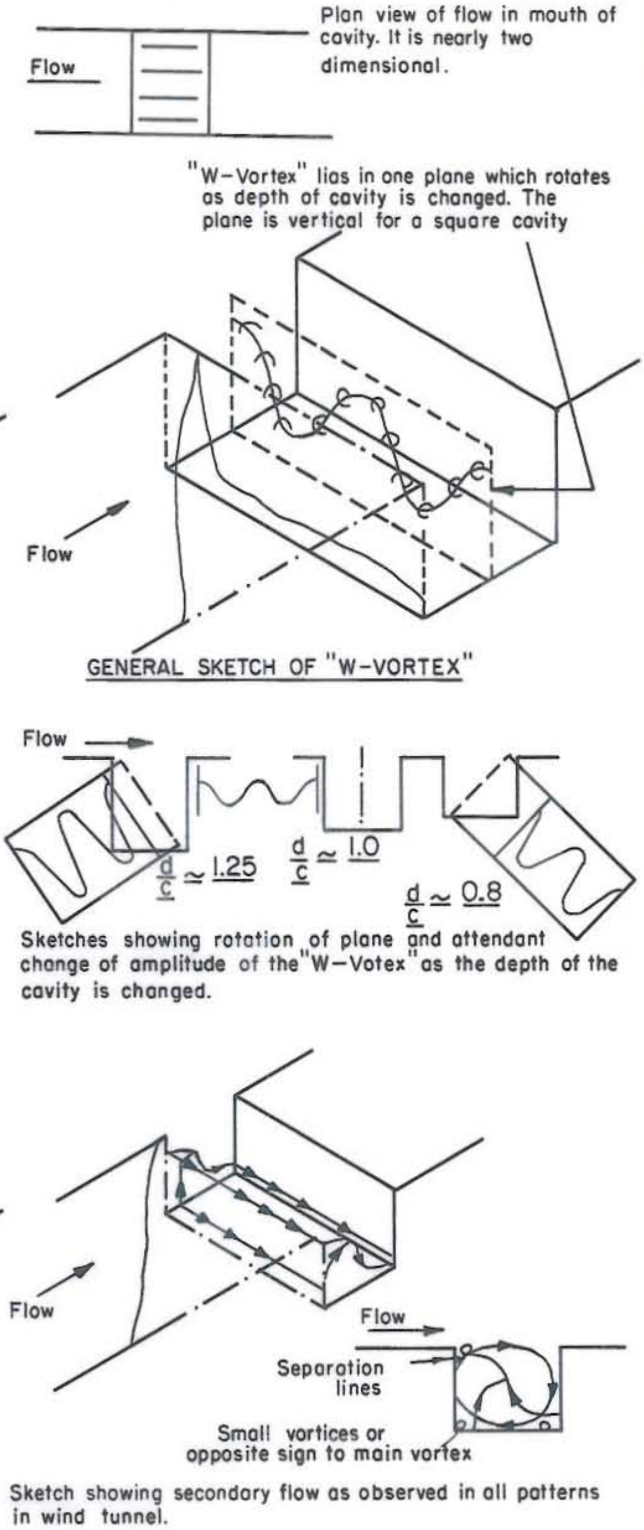


(e) $1.4 \leq h/b \leq 2.4$:-
Two vortices of smaller strength
than the vortex in a square
cavity.

Fig. 4.14 : Flow Regimes in Cavities, Mills (1961)



The alternative flow patterns which occurred at depth chord ratios between 0.8 and 1.25



The W-vortex pattern and associated secondary flow

Fig. 4.15 : Observed flow patterns (Lewis 1966)

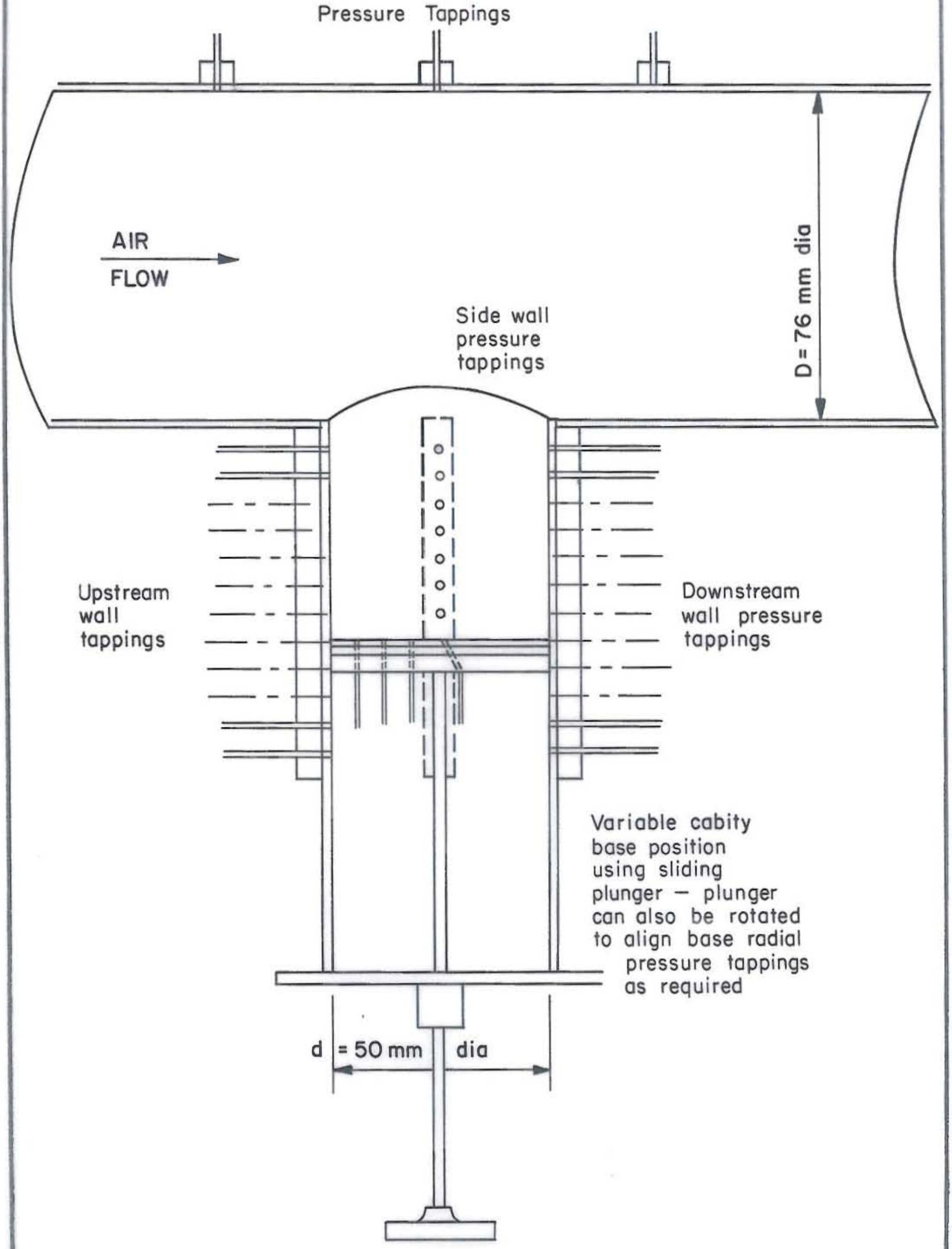


Fig. 4.16 : Model Catchpot (1st Series)

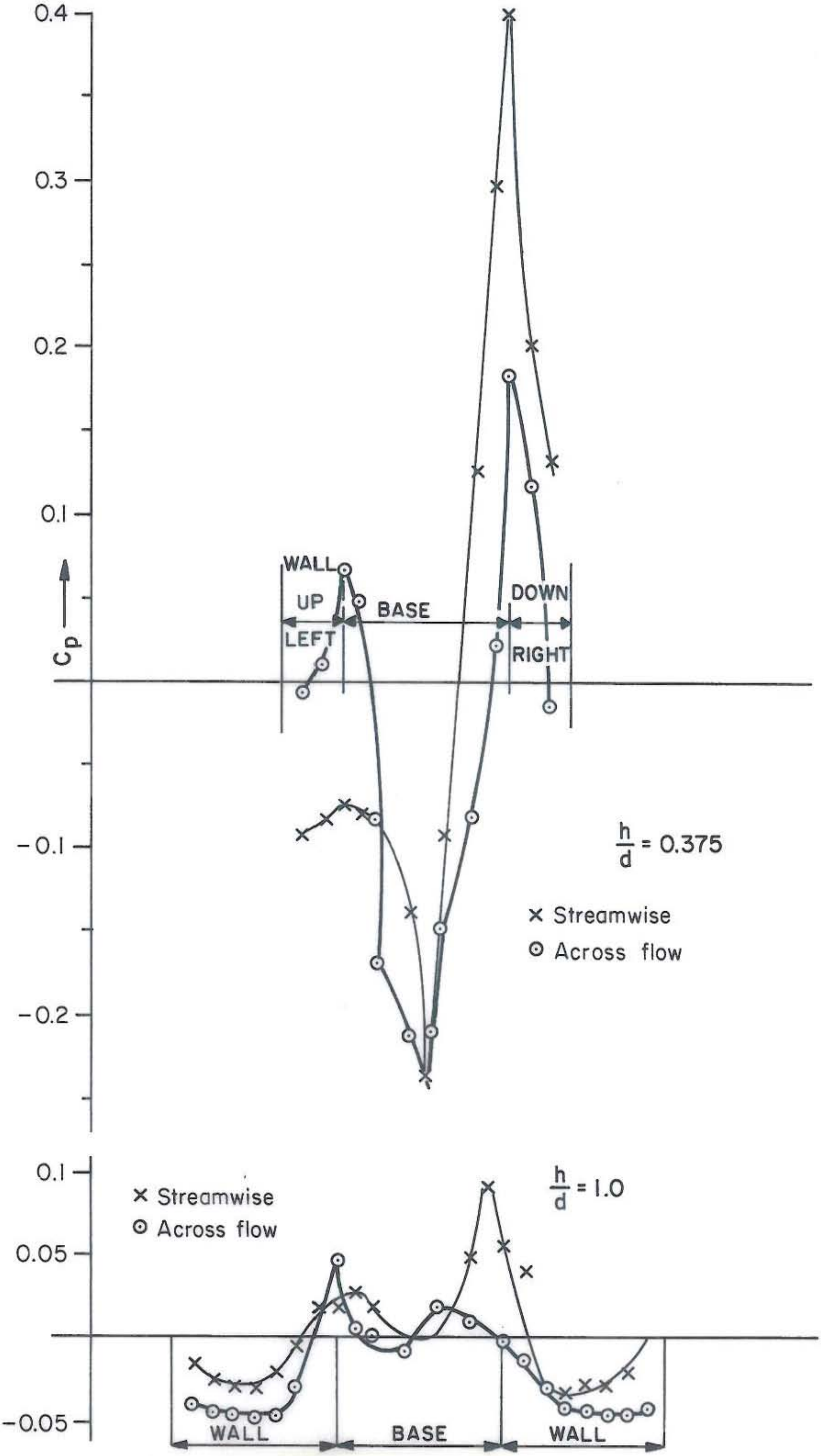


Fig. 4.17 : Typical Cavity Pressure Profiles (Series 1).

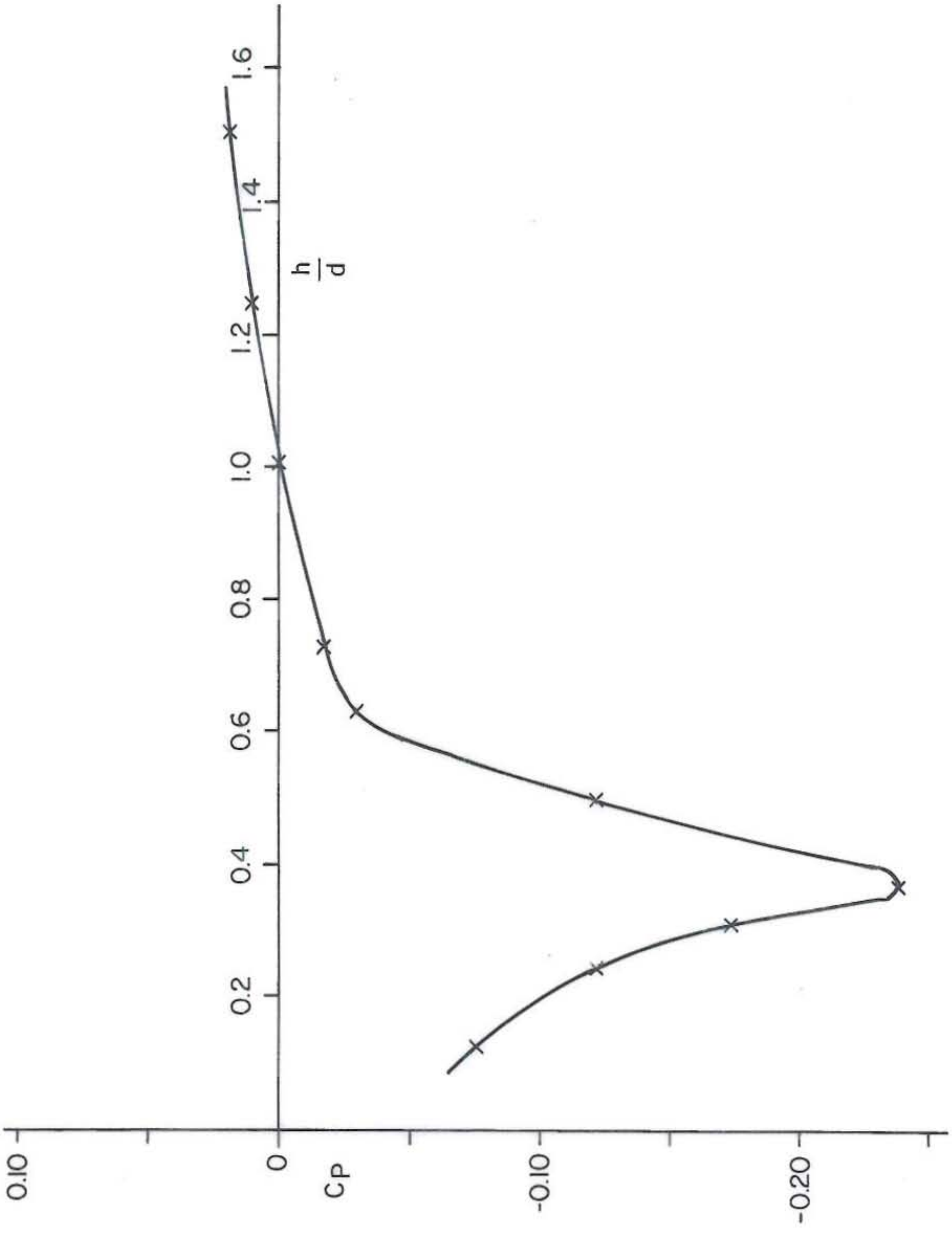


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Fig 4.18 : Base Pressure Coefficient (Series 1)

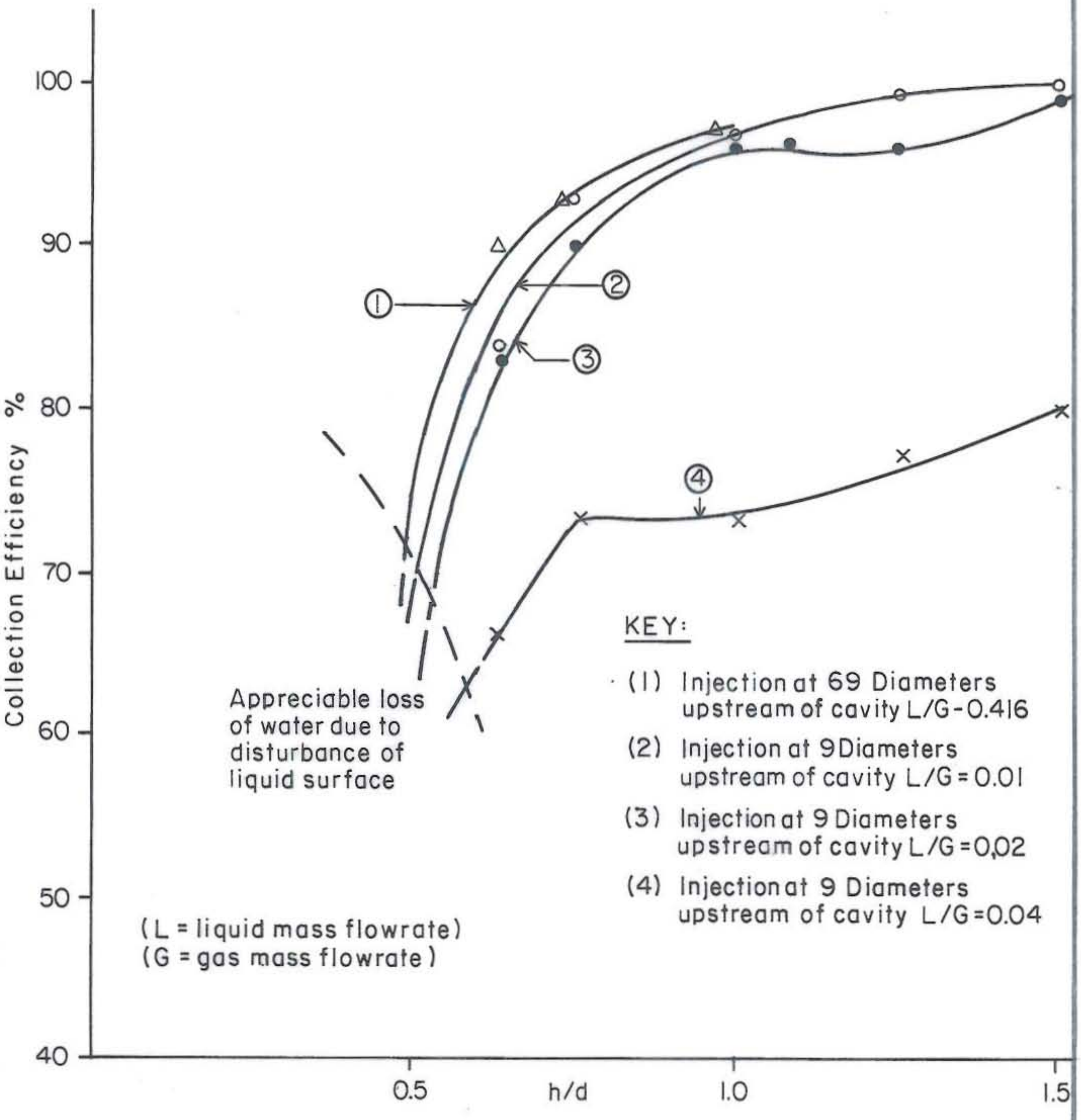

Fig. 4.19 : Collection Efficiency (Series 1)

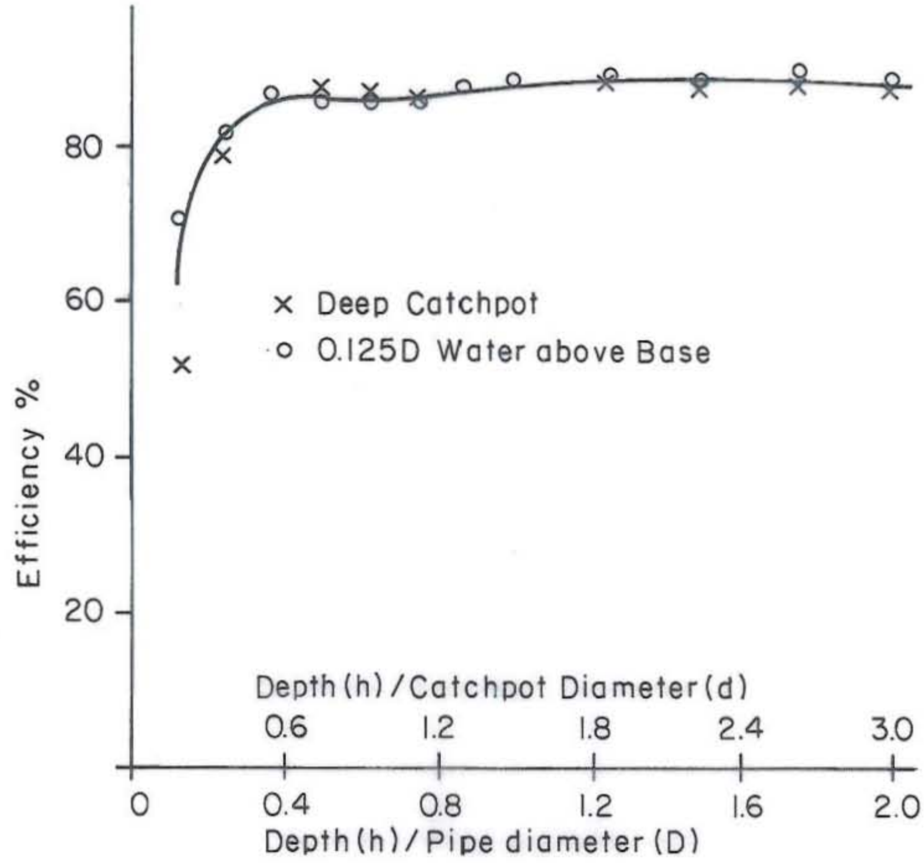

Fig. 4.20 : Catchpot Efficiency $\frac{D}{d} = 1.5$

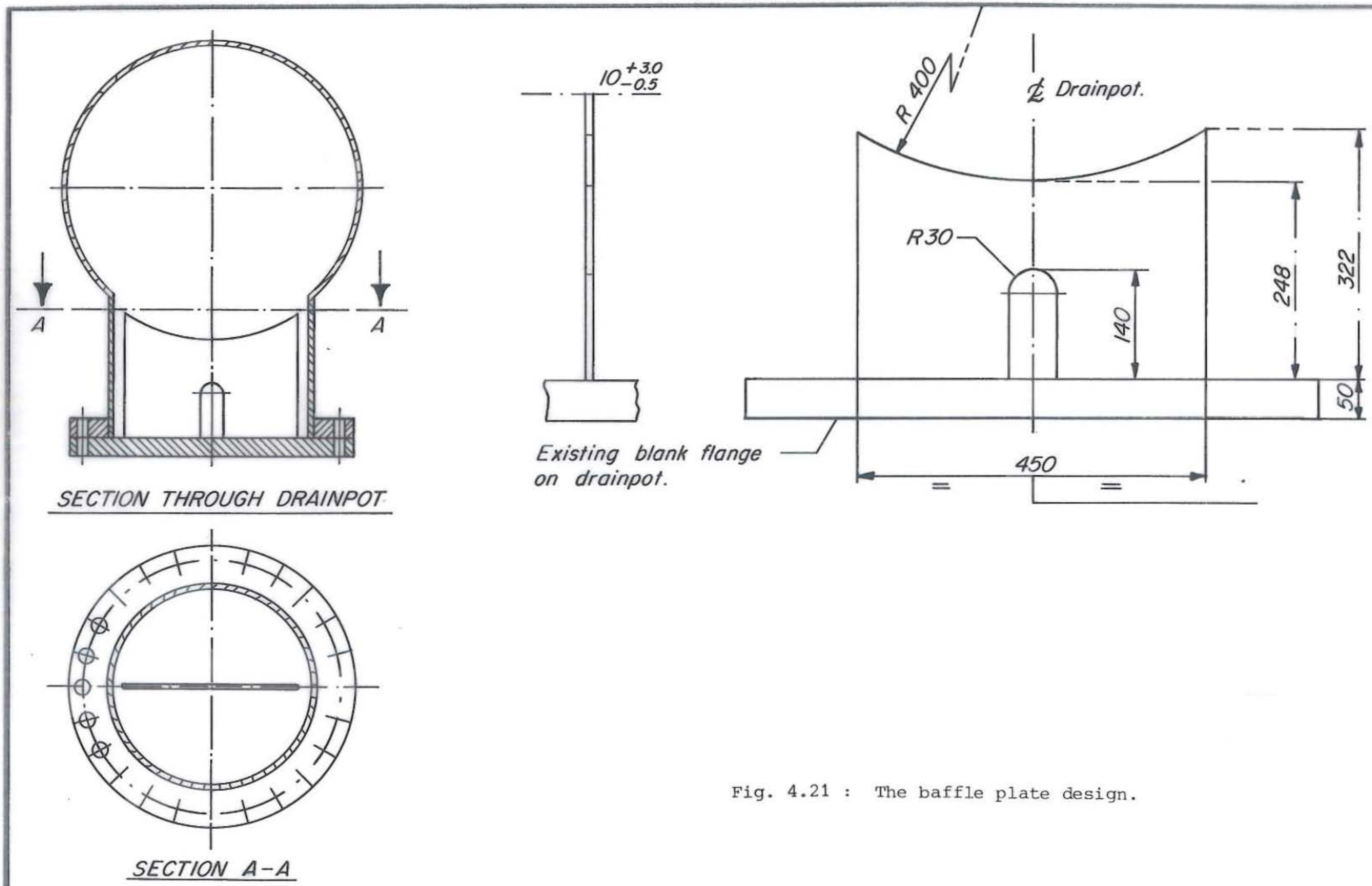

Fig. 4.21 : The baffle plate design.

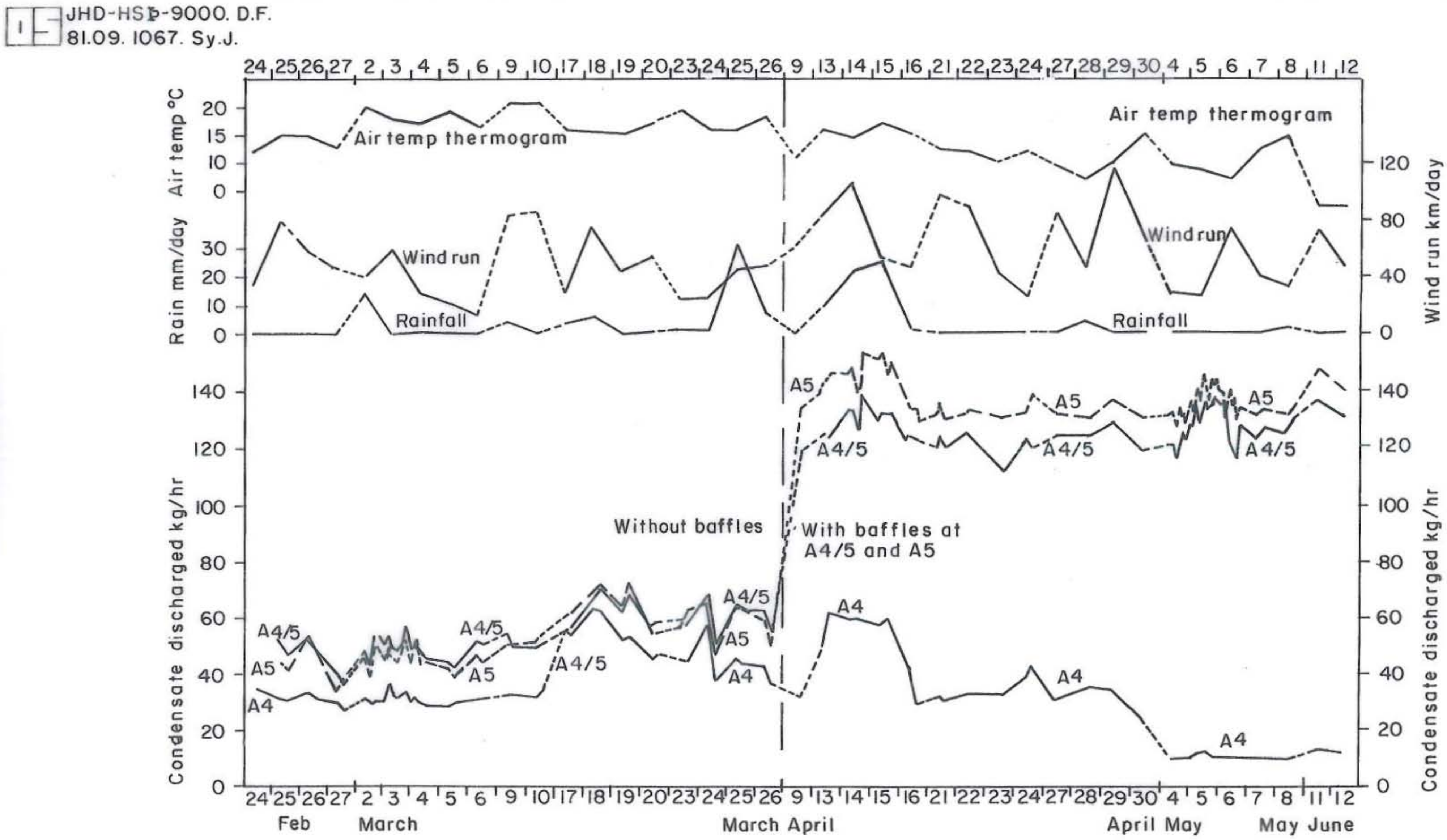

Fig. 4.22 : Measured condensate discharge rates of A4, A4/5 and A5 drainpots before and after the installation of baffles at A4/5 and A5 drainpots of 'L' line (Lee 1981).