REPORT
ON
MASTER PLAN STUDY
FOR
THE DEVELOPMENT OF PETROLEUM AND NATURAL GAS RESOURCES
IN
MALAYSIA

- VOLUME I -
(SCOPE OF MASTER PLAN STUDY)

JANUARY 1978

JAPAN INTERNATIONAL COOPERATION AGENCY

Preface

The Government of Japan, in response to the request of the Government of the Federation of the Malaysia, decided to make an investigation for petroleum industry development program and entrusted the execution of it to the Japan International Cooperation Agency.

The Agency, hoping the said survey would be a help to the Federation of the Malaysia in drawing up its short and long term oil and gas development program and its policy of effective utilization of the said resources in the country, sent, under the cooperation of ministries concerned, such parties as information gathering mission, inception report mission, data analysis mission and site survey mission to the said country, grasped present condition of the Malaysia side and collected necessary data.

After returning to Japan, the above-mentioned missions analized the data, performed feasibility study on technical and economical matters. Hereby presented is a report based upon the outcome of the investigation performed. I belive that the report will serve to the benefits of the Federation of the Malaysia.

Finally, I take this opportunity to express my heartfelt gratitude to the PETRONAS (PETROLIAM NASIONAL BERHAD) and the Japanese Embassy in the Federation of the Malaysia, the Ministry of Foreign Affairs and the Ministry of International Trade and Industry in Japan for their kind cooperation and support extended to our missions.

January 1978

Shinsaku HOGEN
President,
Japan International Cooperation Agency

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1. OBJECTIVES OF THE STUDY

The overall objectives of the Master Plan Study are to make recommendations that will assist PETRONAS to perform the followings;

(a) to prepare a short term and long term development programme for the development of petroleum and natural gas resources; and

(b) to pursue appropriate policies and strategies for the efficient utilization of the resources consistent with the objective of maximizing benefits to Malaysia, and providing for the need for self reliance and self sufficiency in petroleum and petrochemicals.

The scope of work to be performed by JICA includes;

(a) review and assessment, based on the existing available data, of the size of petroleum and natural gas reserves, the areas and data to be examined and the items to be determined being those indicated in Appendix I attached hereto;

(b) review and assessment of existing exploration and production facilities available for the exploitation of Malaysia's petroleum resources and making appropriate recommendations;

(c) review and assessment of the existing practices with regard to the exploitation of petroleum resources and making recommendations for possible improvements.

2. METHODOLOGY

2.1 Evaluation of Oil and Gas Fields and Performance Prediction

(1) Oil and Gas in Place Calculation and Basic Data Compilation

Determinations of geologic structures of reservoirs were made either by geologic analysis through correlation, as for the most producing fields, or by seismic interpretation on seismic sections, as for the others including all non-producing fields. After general stratigraphic study, all reservoir zones of interest were named alphabetically, independently of pre-existing local names.

Available core analysis data were checked in detail to establish the most suitable method of log analysis, which was described in the Appendix V. Log analysis to obtain water saturation and porosity was performed either manually or by the digital computer.

On the basis of the results of geological analysis and quantitative log analysis, fluid properties and their distribution analysis were made. Original hydrocarbons in place were calculated volumetrically for all the fields, the results of which were investigated later for produicng fields when the reservoir simulation was completed.

(2) Reservoir Performance Analysis

The performance analysis was made on each producing field by checking in detail pressure, gas oil ratio and water oil ratio data. General field characteristics and the fluid displacement mechanism were obtained by reviewing the well behaviors and the pressure performances.

Reservoir modelings were made for the reservoir performance predictions by checking the actual well completion systems and field characteristics. Two types of model were applied for the analysis of the produicng fields. One was the VOL33S, the details of which were described in the Appendix III, and the other was the block model, which was used for the reservoir base calculation.

Reservoirs composed of many thin zones had to be handled as single reservoirs by using pseudo-function, especially pseudo-relative permeability relation curve. The reservoir parameters were adjusted by trial and error calculations through the history match procedures till the models represent the reservoir past performances properly.

A determination of the validity of the models was made by the pressure match and the event match, such as the match of producing gas oil ratio, water oil ratio and break-through timing. Finally the oil in place values were reviewed by comparing with those estimated by the volumetric method.

For the analysis of the fields for development and some of the fields in the good prospect area, the conventional material balance method was applied for the estimation of anticipated probable future performance.

Prediction studies consisted of predictions of the future performances of individual reservoir groups under several development cases: extension of the existing conditions and additional wells case. In the additional wells case, maximum allowable production rates from purely technical point of view were estimated for the main producing reservoirs in Malaysia. The case for the development of undrilled area in the producing fields were also made.

Few special core analysis data and very short production histories were available, which did not justify the preferability of water or gas injection, or the necessity of additional energy for the pressure maintenance.

Special emphasis was placed on gathering the data required for determing the most suitable development ways. Optimization of the field base production rates were made in order to maintain comparatively long-term constant rates of production.

In the actual performance analysis, data availability decided the method of the analysis applied to the individual fields. When the history performance was sufficint enough to characterize the reservoir, computation was made at first to match the pressure and GOR/WOR history. However, the reported instantaneous GOR was, sometimes, observed to be not accurate enough to define the transient GOR change, the trial was made to match cumulative produced gas volume.

For the analysis of the field where no pressure data was available and reservoir limit was not confirmed, the decline curve method was applied by assuming the original hydrocarbons in place.

As for the analysis of the fields where the solution gas and gas cap play an important role in the actual oil production, the gas oil relative permeability relation was the most important factor in estimating the reservoir future performance and ultimate recovery. When the relative permeability information was not available, the relation was at first assumed by the data of adjacent same type of the field, then it was modified and adjusted through the history match procedure.

General fluid characteristics of Malaysia oil field was summarized by the use of available special fluid analysis results, which was described in the Appendix IV. The relation was utilized for the estimation of the fluid properties of the field where no fluid data was available.

As for the analysis of Central Luconia gas fields, reservoir base prediction was made for individual fields by establishing the relation of cumulative production vs. average reservoir pressure, and well head pressure vs. flow rates. Recoverable reserves were estimated based on the facilities restrictions and well head pressure as calculated by the Cullender & Smith method.

Several alternative development cases were studied to find out the most efficient development ways.

Production optimization was finally made for establishing the most suitable gas deliverability schedule by developing six gas fields.

2.2 Surface Facilities

(1) Existing Facilities

Eight offshore oil producing fields are situated at four geographical locations in Malaysia as shown in Fig. B-I-1. For the convenience of the execution of study these fields are classified into the following three groups each of which independently handles oil stream from wellhead to tanker loading point.

- Labuan Stream - Sabah Area
- Tembungo Stream - Sabah Area
- Lutong Stream - Sarawak Area

The study has been carried out on the following items for each of these streams:

- Present status of the existing production facilities
- Review on the capacity of the existing production facilities
- Assessment of the facilities capacity for the predicted production scheme
- Assessment on present production practices

Fully utilized for this study are the data collected at Data Collection phase in September, 1976 and Site Survey phase from December, 1976 to January, 1977.

As for Fairley-Baram field it has been excluded from the objective fields for the facilities study, because most of its facilities exist in Brunei and the information on them was not available.

(2) Proposed Facilities

Several alternative cases for the development of oil and gas fields in Sarawak, Sabah and Peninsular areas have been established including the cases for single field development and for the combined development of several fields. Conceptual design for the alternative cases has been carried out in accordance with the production performance predicted in the previous section. As the result of the conceptual design, flow diagrams, facilities layouts and so on have been prepared.

To avoid complexity, facilities description is made only for some selected cases taking into consideration the economic analysis.

There are some fields which should not be handled in the same way as others at this time because of haveing some uncertainty in reserves or having neighboring fields with high possibility of development and being considered to be more profitable if developed with them. For these fields, as detailed discussion is not so meaningful at present, only capital investment costs have been estimated and conceptual design work has been performed as required for this cost estimate. Therefore design documents such as equipment lists, etc. were not prepared.

The objective facilities in this conceptual design include drilling platforms, production platforms submarine pipelines, offshore or onshore oil storage facilities, loading facilities and support facilities for them.

2.3 Cost Estimate and Economic Analysis

(1) Cost Estimate

Capital investment and annual operating cost have been estimated for each of the alternative cases for which the conceptual design of production facilities of the oil and gas fields has been performed. As a result, capital investment schedules have been prepared to be used as basic data for subsequent economic analysis. The capital investment estimate has been performed for production wells drilling cost, offshore platforms cost, submarine pipelines cost, oil and gas production equipment cost, offshore storage and loading facilities cost or onshore storage and loading facilities cost, their support facilities cost, etc. The operating cost has been estimated for operating personnel, chemicals, service contractors, repair and maintenance, insurance and so on required for the field operation of the above-mentioned facilities.

Both estimated capital investment and operating cost are for budget purpose to be used for subsequent economic analysis and those costs are as of middle of 1976.

(2) Economic Analysis

The economic analysis has been performed regarding various production schemes selected for both oil and gas fields in the conceptual design phase. Regarding oil, the profitability of each production scheme is analyzed based on Production Sharing Agreements in Malaysia from the standpoint of Petronas and Operating Company respectively.

Regarding gas, gas costs have been calculated based on the proper formula which was prepared for the purpose to select the lowest cost scheme of gas production and gathering. Gas utilization projects of large scale are generally difficult to decide the execution of them without the consideration of overall profitability for both gas production scheme and utilization scheme. And it is difficult to obtain such a general sales price for gas as that for oil. For this reason, it is not realistic to analyze profitability only for the objective gas production scheme without that for gas utilization scheme. Therefore, in this study the net gas cost has been estimated to deliver the gas to an onshore gas plant. For reference, a calculated example is shown in this study for the gas cost based on Production Sharing Agreement in Malaysia under some assumptions.

Results of economic analysis are also used in the conceptual design phase to eliminate duplicate and unnecessary description of facilities for some of alternative schemes.

This economic analysis consists of the following;

- Economic analysis bases
- Economic evaluation on oil and gas

3. DATA STUDIED

The data list available for the Master Plan Study was submitted to PETRONAS when the presentation of the Inception Report was made.

3.1 Evaluation of Oil and Gas Fields and Performance Prediction

Following data have been utilized in this phase of the study.

- Seismic Record Section
- Well Shooting Data
- Shot Point Map
- Well Completion Report
- Conventional Core Analysis
- Special Core Analysis
- Conventional Gas Analysis
- Special Fluid Analysis
- Pressure and Production History Data
- Well Logs
  - Spontaneous Potential Log
  - Gamma Ray Log
  - Sonic Log
  - Neutron Log
  - Formation Density Log
  - Induction Resistivity Log
  - Latero Log
  - Micro Latero Log
  - Caliper Log

3.2 Surface Facilities

(1) Data Studied for Review and Assessment of the Existing Facilities

Data studied for this study are accurate and realistic data which have been selected out of data collected in "Data Collection" and "Site Survey" phases.

(2) Data Studied for Conceptual Design

In addition with above data studied, data found out from prediction of oil and gas production performance based on the reservoir study have been mainly used for this study.

3.3 Cost Estimate and Economic Analysis

(1) Data Studied for Cost Estimate

Following data have been used.

- Data obtained by the conceptual disign work
- Data from our cost estimate experience

(2) Data Studied for Economic Analysis

Following data have been used.

- Data obtained by cost estimate and conceptual design work

- Data presented from Down Stream Team

4. ENCLOSURES

GLOSSARY OF TERMS

STB; the abbreviation for Stock Tank Barrel. It is an oil volume unit at atmospheric condition (60°F, 14.7 psia).

RB; the abbreviation for Reservoir Barrel. It is a volume unit at reservoir condition.

S.S. DEPTH; the abbreviation for Sub-Sea Depth.

MMSCFD; the abbreviation for million standard cubic feet per day.

BBL; the abbreviation for barrel.

BPD; the abbreviation for barrel per day.

DRILLING PLATFORM; an offshore structure with legs anchored to the sea bottom. The platform, built on a large-diameter pipe frame, supports the drilling of a number of wells from the location.

PRODUCTION PLATFORM; an offshore structure built for the purpose of providing a central receiving point for oil produced in an area of the offshore. The production platform supports receiving tanks, treaters, separators, and pumping units for transmitting the oil through a submarine pipeline.

SALM; the abbreviation for Single Anchor Leg Mooring. It is one of loading facilities of Singe-Bouy-Mooring System.

OIL AND GAS SEPARATOR; a cylindrical vessel used for separating the fluid into liquid and gas respectively. There is two types by purpose namely, vertical and horizontal.

VENT or FLARE LINE; a pipeline installed between production platform and vent or flare jacket for transporting unnecessary gas or gas at urgent time.

ASSOCIATED GAS; a gas produced with crude oil.

FORMATION WATER; the water originally in place in a formation.

ORIGINAL OIL (or GAS) IN PLACE; the amount of crude oil (or gas) that is estimated to exist in a reservoir and that has not been produced.

PAYOUT TIME; payout time is the yardstick by which the majority of all properties are judged. It means the period within which capital investment and other expenses are recovered from production. The primary weakness of this approach is that it does not take into consideration the rate of earnings over the life of the investment nor the life of the investment itself.

SENSITIVITY ANALYSIS; Sensitivity analysis is to calculate the profitability yardstick such as DCF ROR by changing the value of production rate, sales price, investment, etc.

NET CASH FLOW; Net cash flow is the actual profit which is expected to be acquired in the future when investigating a prospective investment.
It does not involve the assumption of an arbitrary discount rate.

DCF ROR; DCF ROR (Discounted net Cash Flow Rate of Return) is the yardstick which is now most widely accepted in pertoleum mining industry. The basic equation is

$$\frac{S1}{(1+i)^{0.5}} + \frac{S2}{(1+i)^{1.5}} + \frac{S3}{(1+i)^{2.5}} + \cdots\cdots$$

$$+ \frac{Sn}{(1+i)^{n-0.5}} = 0$$

Where S = net cash flow in any year
n = life of the property in years
i = DCF ROR

DCF ROR i must be solved by trial and error method. The primary disadvantage is that it is laborious if performed manually. It does, however, have the advantage of showing the effect of time on earnings and accurately reflects how various ways of handling the property will affect the economics.

DISCOUNT RATE; Discounted rate is the rate by which actual profit expected in future is discounted back to the date of the evaluation.

NET PRESENT VALUE; Net present value nomally refers to all future net revenue discounted back to the date of the evaluation, the present. The basic equation is

$$P = \frac{S}{(1+i)^n}$$

Where

P = net present value

S = net cash flow n periods away

n = life of the property in years

i = discount rate for a given period

APPENDIX

APPENDIX

APPENDIX I

Minutes of Discussions, held in Petronas's Offices, Kuala Lumpur, from 11th to 15th July 1976, on the Master Plan Study for the Development of Petroleum Resources in Malaysia

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A Mission from the Japan International Cooperation Agency (JICA) headed by Mr. Yukitoshi Nagasawa, Head, Industry Division, Mining & Industrial Planning and Survey Department of JICA, discussed the Japanese Government's portion of the Study with the Malaysian team headed by Mr. Rastam Hadi, Executive Director, PETRONAS, for the purpose of reaching mutual consent.

After considerable discussions the two parties concurred on the contents of Attachment A to these Minutes. It was also agreed that the portion within the Overall Objectives of the Master Plan Study covered by Item (I) (1) (b) of Attachment A would not be undertaken by JICA as the understanding was that this part of the Study would be performed by C. Itoh in accordance with an Agreement to be separately concluded between PETRONAS and C. Itoh.

It was also explained by Mr. Nagasawa that the aspect of the Study involving the recommendation of policies and strategies for the exploitation of petroleum resources was an integral part of the overall policy recommendations and should not be separated from the other part of the Study. Accordingly the following item:

> " recommending policies and strategies for the exploitation of petroleum resources with a view to ensuring proper conservation and self-sufficiency for the country in the long run "

which originally appeared in the Scope of Work of the Study was deleted from Attachment A on the understanding that this part of the Study would also be undertaken by C. Itoh under the Agreement referred to above.

The Japanese mission agreed to recommend to its own Government the matters referred to in the Minutes of discussions.

Kuala Lumpur, 15th of July, 1976.

For Petroliam Nasional Berhad,

(RASTAM HADI)
Executive Director
PETRONAS

For Japan International Cooperation Agency,

(YUKITOSHI NAGASAWA)
Head of
Industry Division, Mining & Industrial Planning and Survey Department, JICA.

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ATTACHMENT "A"

On this Attachment "JICA" refers to the Japan International Cooperation Agency and "PETRONAS" refers to Petroliam Nasional Berhad.

ITEM I

THE OVERALL OBJECTIVES OF THE MASTER PLAN STUDY

(1) The overall objectives of the Master Plan Study are to make recommendations that will assist PETRONAS to perform the following:-

(a) to prepare a short term and long term development programme for the development of petroleum and natural gas resources; and

(b) to pursue appropriate policies and strategies for the efficient utilization of the resources consistent with the objective of maximizing benefits to Malaysia, and providing for the need for self reliance and self sufficiency in petroleum and petrochemicals.

(2) The Master Plan Study shall be undertaken within the general context of, and consistent with the objectives, goals and targets of the Third Malaysia Plan of the Government of Malaysia.

ITEM II

SCOPE OF WORK

(1) The scope of work to be performed by JICA shall include:-

(a) review and assessment, based on the existing available data, of the size of petroleum and natural gas reserves, the areas and data to be

Y. N. R.H.

examined and the items to be determined being those indicated in Appendix I attached hereto;

(b) review and assessment of existing exploration and production facilities available for the exploitation of Malaysia's petroleum resources and making appropriate recommendations;

(c) review and assessment of the existing practices with regard to the exploitation of petroleum resources and making recommendations for possible improvements.

ITEM III

COLLABORATION OF JICA

(1) JICA shall send a team of experts to Malaysia for the sole purpose of carrying out the study. Their periods of stay in Malaysia shall be dictated by the necessities of the study.

(2) JICA shall submit to PETRONAS the following reports:-

(a) Inception Report.
Ten (10) copies of Inception Report containing proposed study procedures and work schedule within two months after the completion of collecting the data as specified in the appendix.

(b) Interim Report
Ten (10) copies of Interim Report within six months after the date of submission by JICA of the above mentioned Inception Report.

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(c) Draft Final Report
Ten (10) copies of Draft Final Report within four months after the date of submission by JICA of the above mentioned Interim Report.

(d) Final Report
Thirty (30) copies of Final Report within two months after the receipt of the comments on the Draft Final Report.

(3) JICA shall not be responsible for, and PETRONAS shall indemnify and hold JICA harmless against, any claims placed by any third parties resulting from performance under this Master Plan Study except for claims arising from negligence, malfeasance, or misconduct of its experts.

(4) JICA and its employees engaged in this study, and the experts that it has retained shall not, at any time, divulge to any third party any information obtained in the course of its work under this Master Plan Study. Therefore all recommendations made by JICA as a result of the Master Plan Study shall remain confidential unless PETRONAS specifically signified otherwise.

ITEM IV

COLLABORATION OF PETRONAS

(1) PETRONAS shall provide and arrange for JICA to have access to all data, information, documents and reports as may be necessary, in the custody of or available to PETRONAS, relevant to the Master Plan Study.

(2) The Project Director, local counterpart staff and supporting facilities shall be provided by PETRONAS in order to assist JICA and the experts in their work in Malaysia under this Master Plan Study.

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(3) PETRONAS shall make necessary arrangements for JICA personnel and its experts to be provided with the necessary entry and exit visas, residence permits, and other documents necessary for their stay in Malaysia.

(4) Tax and/or duty of any kinds which may be imposed on JICA or its experts under the laws of Malaysia in connection with any activities by JICA and its experts, or on remuneration to JICA and its experts, under this Master Plan Study, or on remittance of the remuneration abroad shall be borne by PETRONAS.

(5) Within one month of the receipt of the Draft Final Report, PETRONAS shall convey to JICA its written comments on the Report.

ITEM V

OWNERSHIP OF DATA, MATERIALS AND REPORTS

All data, information, documents and reports furnished by PETRONAS to JICA for the purpose of implementation of this study and all reports and masters of maps, diagrams, charts, and histograms prepared as part of this study, shall be the property of PETRONAS, and shall not be distributed to any third party except with the specific approval of PETRONAS. They shall be returned to PETRONAS not later than one month after the presentation of the Final Report.

ITEM VI

RESPONSIBILITIES

The Project Director appointed by PETRONAS will have overall responsibility over this study.

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The JICA team will collaborate with the PETRONAS Project Director on the performance of this study.

In view of the need for maintaining consistency and integrity between the JICA's portion and the C. Itoh's portion of the Master Plan Study, the JICA shall set up within its organization a coordination committee consisting of the representatives of the related Government agencies and the C. Itoh.

ITEM VII

MUTUAL CONSULTATION

The Malaysian authorities concerned and the Embassy of Japan in Malaysia will have mutual consultations on matters necessary to the implementation of the Japanese techuical assistance.

APPENDIX I

SCOPE OF STUDY

I. Areas for the study of reserves;

(1) Producing Fields

a) Fields with long-production history;

(i) West Lutong
(ii) Baram
(iii) Baronia
(iv) Bakau

b) Fields with short-production history;

(i) Tukau
(ii) *Fairley-Baram
(iii) Tembungo
(iv) Samarang

(2) Fields for Development

These are fields in which has been discovered petroleum that can be exploited commercially. The fields are;

a) Sabah and Sarawak

(i) *Central Luconia
(ii) Temana
(iii) Betty
(iv) Bokor
(v) Erb West
(vi) South Furious

b) Peninsular Malaysia;

(i) Pulai
(ii) Bokok
(iii) Sotong

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(iv) Duyong
(v) Anding

(3) Areas with Good Prospects

These are areas in which hydrocarbons have been discovered but commercial viability for exploitation is uncertain.
The areas are:

a) Sabah and Sarawak

(i) Erb South
(ii) St. Joseph
(iii) West Emerald
(iv) Beryl
(v) Siwa

b) Peninsular Malaysia

(i) Seligi
(ii) Belumut
(iii) Peta
(iv) Besar
(v) Angsi
(vi) Bujang
(vii) Sepat
(viii) Jerneh
(ix) Bintang
(x) Tapis
(xi) Pilong

(4) *Priority Areas

It is required that the following fields be given priority treatment;

a) Fairley-Baram
b) Central Luconia.

II. The study will involve examination and collation of the following data:

(1) Surface geology
(2) Geophysics (magnetic, gravity, seismic)
(3) Exploration development and production well data (stratigraphy, petrophysics, lithology, well logs, results of tests and other data as necessary or appropriate).
(4) Reservoir data
(5) Production data
(6) Data relating to existing field facilities including hydrographic and meteorological data.

III. The above data and other relevant data, as may be necessary or appropriate, will be interpreted and the following determined:

(1) Geological and geophysical studies involving lithology, paleontology, well log interpretation, seismic interpretation, etc.

(2) Source rock evaluation.

(3) Hydrocarbon trapping mechanism in the area.

(4) Geological description of fields.

(5) Hydrocarbon characteristics.

(6) Reserves (hydrocarbons in place, proven, probable, possible and recoverable).

(7) Maximum allowable production rate of wells.

(8) MER of reservoirs.

(9) Forecasts of future production including secondary and tertiary recovery.

(10) Feasibility and cost study of petroleum production for the fields.

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APPENDIX II

Summary of PS Agreements and Calculation Items and Formulas for Profitability on Oil

Appendix II

Summary of PS Agreements and Calculation Items and Formulas for Profitability on Oil

A. Summary of PS Agreements

Summary of PS Agreements for bases of economic analysis is as follows;

1. Duration of Agreements

1) Basic Exploration Period:

The basic exploration period is 3 years with an extendable period of 2 years for both oil and gas.

2) Development Period:

The development period is 2 years with an extendable period of 2 years for both oil and gas. However gas is allowed a waiting period of up to 5 years before development.

3) Production Period:

The production period is 15 years for both oil and gas. However gas is allowed an extendable period of 5 years.

2. Royalty:

Operating Company is to pay 10 per cent royalty which is to be shared equally between the Federal and the State Governments.

3. Cost Oil and Gas:

Operating Company is allowed recovery of cost of 20 per cent for exploration, development and production of oil and 25 per cent of gas.

4. Profit Oil and Gas:

What is left after cost recovery and royalty will be shared on the basis of 70 per cent for Petronas and 30 per cent for the Operating Company for both oil and gas.

5. Basic Price:

When the price of oil exceeds the basic price of US $12.72 per barrel, Operating Company has to surrender 70 per cent of the proceeds from the sales of profit oil above the basic price to Petronas. The basic price will be allowed an increase of 5 per cent once a year.

6. Research Fund:

Operating Company will have to contribute 0.5 per cent of the proceeds from the sales of cost and profit oil and gas to Petronas for the purposes of research.

7. Bonus:

1) Discovery Bonus

Operating Company will pay a discovery bonus of M$ 2.5 million to Petronas for every discovery of new commercially viable oil field.

2) Production Bonus

Operating Company is to pay a production bonus of M$ 5 million to Petronas every time their average daily oil production increases by 50,000 barrels a day.

8. Income Tax:

Both Petronas and Operating Company will have to pay 45 per cent petroleum income tax. The tax will be assessed on corporate entity with the usual allowances.

B. Calculation Items and Formulas for Profitability of Oil

Calculation items and formulas for profitability of oil based on PS Agreements are as follows;

1. Cost Recovery

Operating Company is allowed cost recovery of 20 per cent of oil production for investment cost and operating cost in accordance with PS Agreements. Cost recovery is calculated as follows;

1) Unrecovered Period of Investment Cost

Cost recovery is 20 per cent of oil production for investment cost and operating cost.

2) Period after Recovery of Investment Cost

Cost recovery is only for operating cost. However, cost recovery must not exceed 20 per cent of total oil.

2. Profit Oil Ratio for Petronas and Operating Company

(1 - Royalty Rate - Cost Recovery Ratio) x Profit Oil Share

3. Equity of Operating Company

Capital Investment x Equity Ratio

The investment cost other than equity is considered to be covered by bank borrowing. Its interest is calculated separately from the cash flow for ROR calculation.

4. Cash Flow for Petronas

1) Cash Inflow by Year

a. Sales Revenue from Profit Oil:

Total Sales Quantity of Oil x Profit Oil Ratio of Petronas x Sales Price of Oil

b. Revenue from Oil Related to Basic Price:

This item is calculated in cash flow for Operating Company.

c. Bonus from Operating Company:

(i) Discovery Bonus: from input data

(ii) Production Bonus: from cash flow for Operating Company

d. Research Fund from Operating Company:

This item is calculated in cash flow for Operating Company.

2) Cash Outflow by Year

a. Income Tax:

Cash Inflow x Tax Rate

3) Net Cash Flow by Year:

Cash Inflow - Cash Outflow

4) Cumulative Net Cash Flow by Year

5) Present Worth by Year:

a. Present Worth for each Discount Rate

b. Cumulative Present Worth for each Discount Rate

5. Cash Flow for Operating Company

1) Cash Inflow by Year

a. Sales Revenue from Profit Oil:

Total Sales Quantity of Oil x Sales Price of Oil x Profit Oil Ratio of Operating Company

b. Sales Revenue from Cost Oil:

Total Sales Quantity of Oil x Cost Recovery Ratio
x Sales Price of Oil

c. Sales Revenue from Royalty Oil:

Total Sales Quantity of Oil x Royalty Rate
x Sales Price of Oil

2) Cash Outflow by Year

a. Royalty:

Sales Revenue of Total Oil x Royalty Rate

b. Payment Related to Oil Basic Price:

Sales Quantity of Profit Oil x (Sales Price - Basic Price) x Rate of Payment for Profit Oil

Note: Basic Price = Initial Basic Price
x (1 + Rate of Increase)

If the value of
Sales Price - Basic Price
is less than zero, this value is zero.

c. Bonus:

(i) Discovery Bonus: from input data

(ii) Production Bonus:

Production bonus is to pay M$5,000,000 to Petronas every time average oil production increases by 50,000 barrels a day. Otherwise, if average daily oil production is less than 50,000 barrels a day, production bonus is equal to zero.

d. Research Fund to Petronas:

Total Sales Revenue of Operating Company
x Rate of Payment for Research Fund

e. Capital Investment: from input data

f. Operating Cost: from input data

g. Annual Operating Expense:

Investment Cost Recovery + Operating Cost

h. Operating Cost per Barrel:

Annual Operating Expense/Annual Oil Production

i. Income before Tax:

Sales Revenue from Profit Oil-Bonus-Research Fund

j. Income Tax:

Income before Tax x Tax Rate

k. Total Cash Outflow:

Royalty + Payment Related to Oil Basic Price + Bonus
+ Research Fund + Operating Cost + Income Tax
+ Capital Investment

3) Net Cash Flow by Year:

Cash Inflow - Cash Outflow

4) Cumulative Net Cash Flow

5) DCF ROR of Net Cash Flow by Year:

The value (= x) is calculated by the following formula;

$$\sum_{i=1}^{n} \frac{\text{Net Cash Flow}}{(1 + x)^{i-0.5}} = 0 \quad (n\text{: year})$$

6) Present Worth by Year

a. Present Worth for each Discount Rate

b. Cumulative Present Worth for each Discount Rate

APPENDIX III

Three-Phase Three-Dimensional Volumetric Reservoir Simulation

VOL33S

THREE-PHASE THREE-DIMENSIONAL

VOLUMETRIC RESERVOIR SIMULATOR

TABLE OF CONTENTS

1. INTRODUCTION

This booklet is to introduce a three-dimensional, three-phase reservoir simulator VOL33S developed and in service in the PERD (a division of Japan Oil Engineering Co., Ltd., Tokyo, Japan). This simulator is designed for studying oil and gas reservoirs with any types of driving mechanisms such as depletion drive, gas cap drive, water flooding and gas injection, so long as the fluid properties can be described simply by the reservoir pressure. By inserting in the simulator, porosity, permeability, fluid properties, initial fluid saturations, initial reservoir pressures and well informations, the reservoir performance along the production schedule is simulated. The future pressure and saturation distributions and production statistics are printed out periodically.

Many accessory sub-programs are available. They are useful in the preparation of the input of VOL33S by the statistical processing of the field data and in visualizing the calculated reservoir performances by the plotter. Various kinds of problems have been solved with this simulator in the past. An example is seen in Reference 1.

In the following chapters, the principle of the simulator will be explained.

2. FEATURES

The features of this simulator are as follows:

(1) The flow of water, oil and gas through petroleum reservoirs are described by the equations of conservation of mass, and the equations are solved by means of the finite difference method.

(2) Darcy's law for fluid flow through porous media is assumed to hold.

(3) The phase behavior of reservoir fluids are assumed to be described accurately by means of the gas and oil formation volume factors and the solubility of gas into oil, and all the fluid properties are determined as functions of pressure and bubble point pressure.

(4) The bubble point pressure in the initial state can be treated variable with location. It can decrease but cannot increase.

(5) The porosity of reservoir rock is assumed not to change with the change in reservoir pressure.

(6) The capillary pressures between phases are assumed to be negligible.

(7) The simulation can be performed in various unit systems.

(8) The simulator can be equipped with a pressure maintenance subroutine which adjusts production or

injection rate of indivisual well so that the reservoir pressure is kept unchanged and the field wide oil production rate is maintained at a specified value as long as the well production capacities allow.

3. EQUATIONS AND RELATIONS DESCRIBING FLUID FLOW THROUGH POROUS MEDIA

3.1 Differential Equations

The law of conservation of mass for water, oil and gas is described in the following mathematical expressions.

$$- \nabla uw\ bw - qw = \frac{\partial(\phi Swbw)}{\partial t} \tag{1}$$

$$- \nabla uo\ bo - qo = \frac{\partial(\phi Sobo)}{\partial t} \tag{2}$$

$$- \nabla ug\ bg - \nabla(uo\ bo\ Rs) - qg = \frac{\partial}{\partial t}(\phi Sg\ bg + \phi So\ bo\ Rs) \tag{3}$$

The meaning of operator ∇ is explained in the nomenclature. When Darcy's law is assumed to hold, u's in Equations (1) through (3) for each phase are substituted by the equations

$$ux = - \frac{Kxkr}{\mu}\left(\frac{\partial P}{\partial x} - \gamma\frac{\partial D}{\partial x}\right) \tag{4}$$

$$uy = - \frac{Kykr}{\mu}\left(\frac{\partial P}{\partial y} - \gamma\frac{\partial D}{\partial y}\right) \tag{5}$$

$$uz = - \frac{Kzkr}{\mu}\left(\frac{\partial P}{\partial z} - \gamma\frac{\partial D}{\partial z}\right) \tag{6}$$

and Equations (7), (8) and (9) are derived.

$$\nabla\frac{Kkrwbw}{\mu w}(\nabla P - \gamma w\nabla D) - qw = \frac{\partial}{\partial t}(\phi Swbw) \tag{7}$$

$$\nabla\frac{Kkrobo}{\mu o}(\nabla P - \gamma o\nabla D) - qo = \frac{\partial}{\partial t}(\phi Sobo) \tag{8}$$

$$\nabla\frac{Kkrgbg}{\mu g}(\nabla P - \gamma g\nabla D) + \nabla\frac{KkroRsbo}{\mu o}(\nabla P - \gamma o\nabla D)$$

$$-qg = \frac{\partial}{\partial t}(\phi Sgbg + \phi SoRsbo) \tag{9}$$

3.2 Relations

3.2.1 Fluid Saturations

By definition, water, oil and gas saturations yield

$$Sw + So + Sg = 1 \qquad (10)$$

3.2.2 Reservoir Fluid Properties

Fluid properties in Equations (7), (8) and (9) are determined as follows:

(1) The formation volume factor and viscosity of water and gas phases are calculated as functions of the reservoir pressure only.

(2) The formation volume factor and viscosity of oil phase are determined differently according to whether the reservoir pressure is lower or higher than the bubble point pressure: if the reservoir pressure is lower, they are determined simply as functions of the reservoir pressure, if the reservoir pressure is higher, they are determined by

$$B_o = B_{o\ \text{bubble point}} - \text{constant}\ (P-P_{\text{bubble point}}) \qquad (11)$$

$$\mu_o = \mu_{o\ \text{bubble point}} + \text{constant}\ (P-P_{\text{bubble point}}) \qquad (12)$$

(3) The solubility of gas into oil is determined as a function of the reservoir pressure for the reservoir pressure lower than the bubble point pressure, and it is assigned to the solubility at the bubble point for the

reservoir pressure higher than the bubble point pressure.

(4) The fluid column pressures are calculated from other fluid properties by

$$\gamma w = \gamma ws/Bw \qquad (13)$$

$$\gamma o = (\gamma os + Rs\gamma gs)/Bo \qquad (14)$$

$$\gamma_g = \gamma gs/Bg \qquad (15)$$

3.2.3 Relative Permeabilities

The relative permeabilities in three phase regions are determined by the following relations*2:

$$krw = krw\ (Sw) \qquad (16)$$

$$kro = krow\ (Sw) \cdot krog\ (Sg)\ \frac{So\ (1 - Swc)}{(1 - Sw)(1 - Swc - Sg)} \qquad (17)$$

$$krg = krg\ (Sg) \qquad (18)$$

3.3 Initial and Boundary Conditions

The initial conditions are the initial distributions of the reservoir pressure, fluid saturation and bubble point pressure. As for the boundary conditions, no cross flow across the reservoir boundaries is employed.

4. SOLUTION OF EQUATIONS BY THE FINITE DIFFERENCE METHOD

4.1 Difference Equations

In applying the finite difference method, the reservoir is divided into a large number of small cells and the cells are numbered as shown in Figure 1. The time is also discretized into intervals of Δt. When the differential operators are approximated by the difference operators

$$\frac{\partial}{\partial t} A) \sim (A_{n+1} - A_n) / \Delta t \tag{19}$$

$$\frac{\partial A}{\partial x}\frac{\partial P}{\partial x} \sim [A^n{}_{i+\frac{1}{2}} \frac{(P_{i+1}-P_i)^{n+1}}{(\Delta X_{i+1}+\Delta X_i)/2} - A^n{}_{i-\frac{1}{2}} \frac{(P_i-P_{i-1})^{n+1}}{(\Delta X_i+\Delta X_{i-1})/2}]/\Delta X_i \tag{20}$$

and the similar operators for the y and z directions, differential equations (7), (8) and (9) are reduced to the difference equations

$$BV\Delta_t(\phi Swbw) = \Delta T_w{}^n \ (\Delta P^{n+1} - \gamma^n{}_w \Delta D)\Delta_t - Qw\Delta_t \tag{21}$$

$$BV\Delta_t(\phi Sobo) = \Delta T_o{}^n \ (\Delta P^{n+1} - \gamma^n{}_o \Delta D)\Delta_t - Qo\Delta_t \tag{22}$$

$$BV\Delta_t(\phi Sgbg + SoboRs) = [\Delta T_g{}^n(\Delta P^{n+1} - \gamma^n{}_g \Delta D) + \Delta(ToRs)^n$$

$$(\Delta P^{n+1}{}_o - \gamma^n{}_o \Delta D)]\Delta_t - Qg\Delta_t \tag{23}$$

In the above and following difference equations, the subscripts i, j, k are omitted for clarity. The intercell transmissibility T, fluid column pressure γ and gas solubility into oil Rs which specify the fluid flow between cells are given by the relation

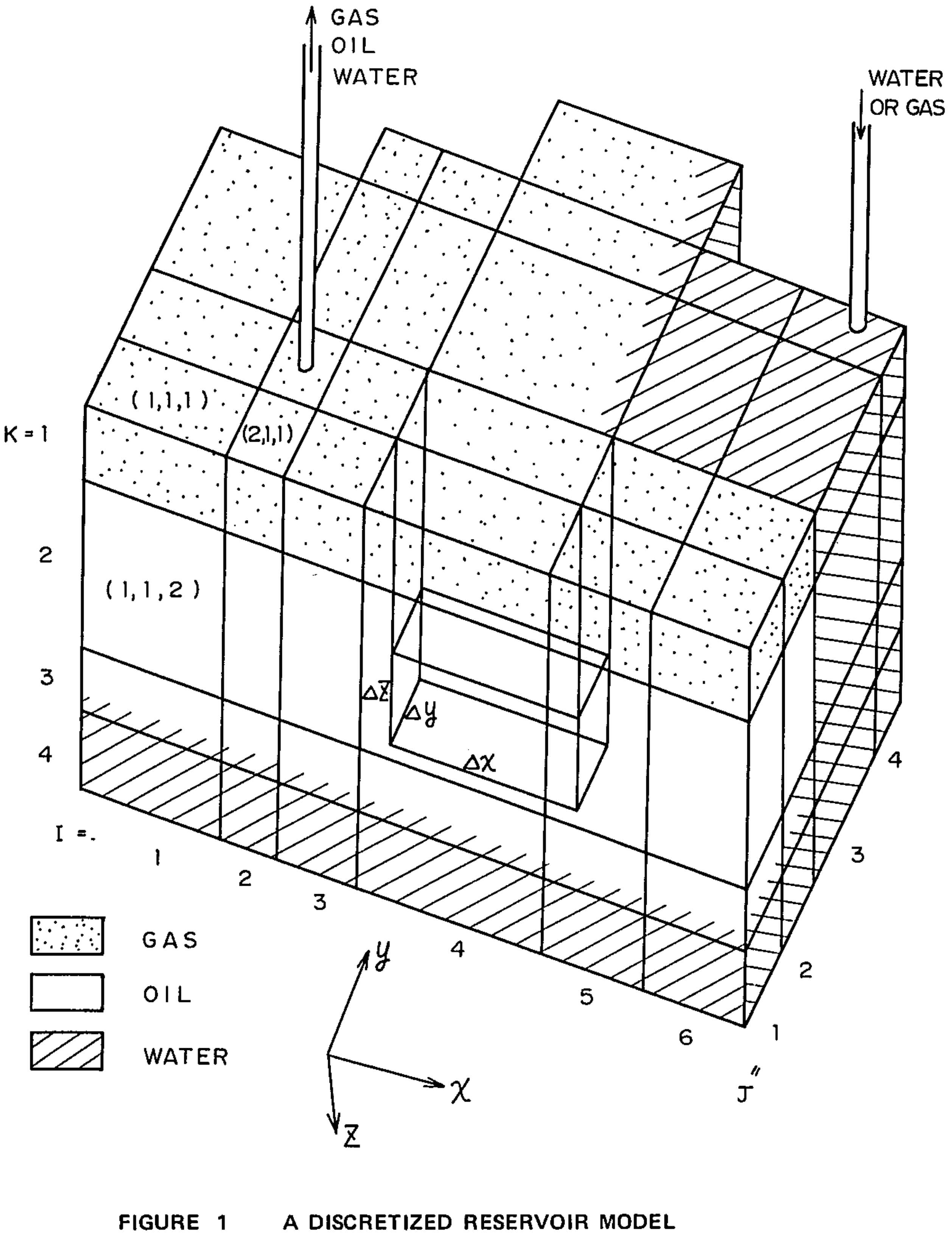


FIGURE 1 A DISCRETIZED RESERVOIR MODEL

$$(TxRs\gamma)_{i+\frac{1}{2}} = [(\frac{krb}{\mu})_{upstream}\frac{2K_iK_{i+1}\ \Delta y\Delta z}{K_i\Delta X_{i+1}+K_{i+1}\Delta X_i}]$$

$$Rs_{upstream}(\frac{\gamma_i+\gamma_{i+1}}{2}) \qquad (24)$$

for the x direction and the similar relations for the y and z directions. The subscript "upstream" refers to the cell i or i+1 where the potential $(P-\gamma_{i+\frac{1}{2}}D)$ is greater than the other one at time t_n.

4.2 Bottom Hole Pressure and Production Rates

4.2.1 Bottom Hole Pressure

The bottom hole pressure is calculated from the cell pressure by Equation (25) assuming a radial semi-steady state flow with a correction factor C.

$$P_{bh} = P - \frac{1}{C} Q_{or\ KA}\frac{\mu_o(\ell n\ \frac{r_e}{r_w} - \frac{3}{4})}{\pi\{h(K_x + K_y)k_{ro}\}_{KA}} \qquad (25)$$

4.2.2 Production and Injection Rates

At production wells, either the stock tank oil production rate or the water-oil-gas total production rate in reservoir conditions is specified and then the production rate for each phase and each cell perforated is determined in proportion to (mobility × effective thickness) at time t_n.

However, the employment of fluid mobilities at time t_n in the calculation of the gas production rate often results in the vibration of gas saturation with time at production cells. This vibration can be avoided by using the following gas production rate:

$$Q_{gk} = [Q^n{}_g + (\frac{\partial Q_g}{\partial S_g})^n \Delta_t S_g]_k \qquad (26)$$

It is also made possible in this simulator to specify the production rate of each phase considering the perforation intervals and well locations within the cell by use of the relative permeabilities specific to each well.

At injection wells, the injection rate of each well is specified by the input data, and the rate then is allocated to each cell perforated to the well in proportion to (total mobility × effective thickness) at time t_n.

4.3 Solution of Equations

Equations (10), (21), (22) and (23) contain four unknowns P, Sw, So and Sg, and are solved as follows. Multiplying a factor $a1 = (\frac{B_w}{Bo - RsBg})_{n+1}$ to Equation (21) and a factor $a3 = (\frac{B_g}{Bo - RsBg})_{n+1}$ to Equation (23) and summing up the resulting equations and Equation (22) give a difference equation where the fluid saturations at time level n+1 appear only in the form of

$(Sw + So + Sg)_{n+1}$. Thus, in right of Equation (10), S_{n+1}'s are eliminated from this equation and Equation (26) which has only one unknown P_{n+1} follows.

$$\phi BV\{a1 \cdot S_{wn}\Delta_t(bw) + S_{on}\Delta_t(bo) + a3 \cdot S_{gn}\Delta_t(bg) + a3 \cdot S_{on}\Delta_t(boRs)\} = -(a1 \cdot Q_w + Q_o + a3Q_g)\Delta t + \{a1 \cdot \Delta T_w(\Delta P - \gamma_w \Delta D) + \Delta T_o(\Delta P - \gamma_o \Delta D) + a3 \cdot \Delta T_g(\Delta P - \gamma g \Delta D) + a3\Delta T_o R_s(\Delta P - \gamma_o \Delta D)\}\Delta_t \qquad (26)$$

The left side terms are now expanded by an iterative scheme

$$\Delta_t A = \left(\frac{A_m - A_n}{P_m - P_n}\right)(P_{m+1} - P_n) \qquad (27)$$

for an iteration step m+1 at time level n+1. This equation is constructed for each cell and the set of equations thus obtained is solved by an alternating-direction method explained in reference 3, given the pressure and saturations at time level n in each cell. The terms containing fluid properties at time level n+1 is updated during the iteration process. Once the set of equations is solved for pressures P_{n+1}, saturations S_{n+1}'s are calculated explicitly by Equations (21), (23) and (10). This procedure is started from time level 1 and is repeated step by step, giving the approximate solutions to Equations (7), (8), (9) and (10).

5. COMPUTER PROGRAM

The above explained computation procedure is coded in FORTRAN IV electric computer language. The number of cells up to 4000 is possible with the IBM 360-195 computer system. The computation time necessary to calculate one time step is variable according to the type of problems and the allowable computation errors and is 0.0010 - 0.0030 central processing sec/cell with this computer system.

NOMENCLATURE

B = formation volume factor in cuft/cuft

b = 1/B = inverse of formation volume factor in cuft/cuft

BV = bulk volume of cell in cuft

C = $(PI)_{actual}/(PI)_{computational}$

D = Depth in ft

h = effective thickness in ft

Kx, Ky, Kz = absolute permeability in the x, y and z directions, respectively in md × 0.00633

kr = relative permeability in fraction

k_{rog} = relative permeability to oil in the oil-gas system in fraction

k_{row} = relative permeability to oil in the oil-water system in fraction

P = reservoir pressure in psia

P_b = bubble point pressure in psia

P_{bh} = bottom hole pressure in psia

q = production rate from one bulk volume of reservoir in cuft/day/cuft

Q_ℓ = production rate of phase ℓ in the surface conditions in cuft/day

Q_{ro} = oil production rate in the reservoir conditions in cuft/day

R_s = solution gas oil ratio in vol/vol

$r_e = \sqrt{\Delta x_i \ \Delta y_j / \pi}$ in ft

r_w = well bore radius in ft

S = fluid saturation in fraction

S_{wc} = connate water saturation in fraction

T = intercell transmissibility

t = time in days

u = flow velocity in ft/day

x = length in x direction in ft

y = length in y direction in ft

z = length in z direction in ft

$\Delta t = t_{n+1} - t_n$ in day

Δx = length of cell in x direction in ft

Δy = length of cell in y direction in ft

Δz = length of cell in z direction in ft

ϕ = porosity in fraction

γ = fluid column pressure in psi/ft

μ = viscosity in cp

Subscripts and Superscrips

g = gas

i = cell number in x direction

j = cell number in y direction

k = cell number in z direction

KA = the cell number of the uppermost perforated

ℓ = subscript denoting w, o or g

m = iteration step

n = time level

o = oil

s = surface condition

w = water

x, y, z = subscripts denoting the direction as shown in FIGURE 1

Operators

$$\nabla A = \frac{\partial Ax}{\partial x} + \frac{\partial Ay}{\partial y} + \frac{\partial Az}{\partial z}$$

$$\nabla A \nabla P = \frac{\partial}{\partial x} Ax \frac{\partial}{\partial x} P + \frac{\partial}{\partial y} Ay \frac{\partial}{\partial y} P + \frac{\partial}{\partial z} Az \frac{\partial}{\partial z} P$$

$$\begin{aligned} \Delta T \Delta P = {} & Txi{+}\tfrac{1}{2} \; (Pi{+}1 - Pi) - Txi{-}\tfrac{1}{2} \; (Pi - Pi{-}1) \\ & + Tyj{+}\tfrac{1}{2} \; (Pj{+}1 - Pj) - Tyj{-}\tfrac{1}{2} \; (Pj - Pj{-}1) \\ & + T_{zk+\frac{1}{2}} \; (Pk{+}1 - Pk) - T_{zk-\frac{1}{2}} \; (Pk - Pk{-}1) \end{aligned}$$

$$\Delta_t A = A_{n+1} - A_n$$

In the above difference equations the subscripts i, j and k are omitted for clarity.

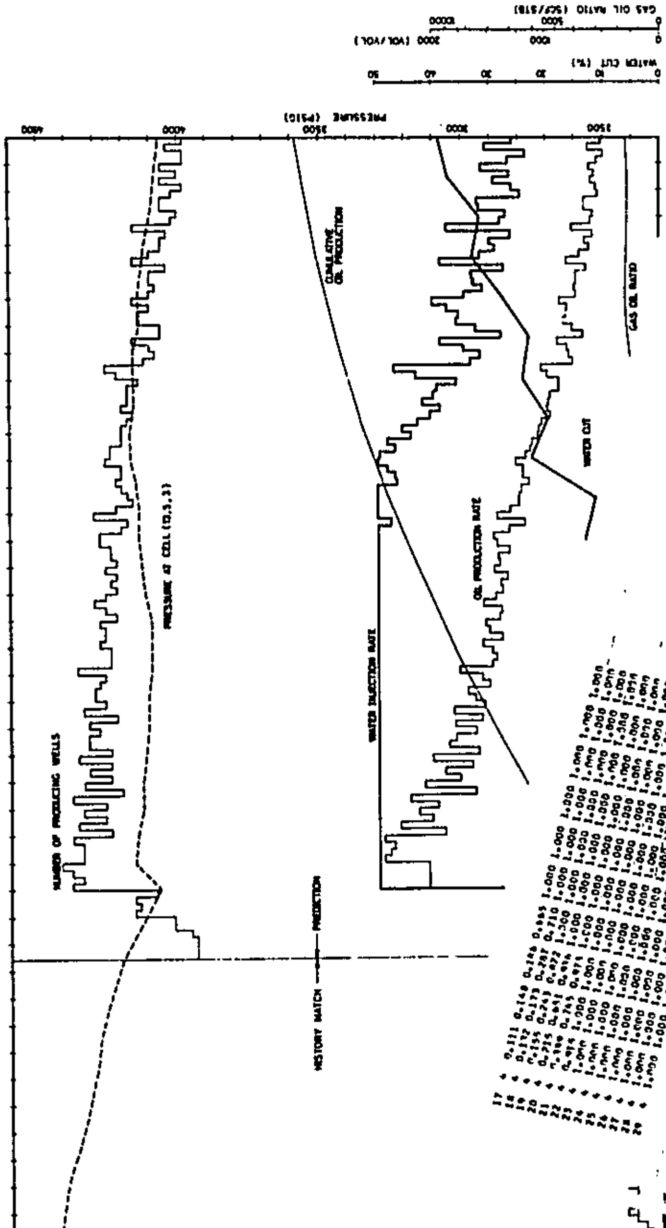
REFERENCE

1. Tsutsumi, G.: "Reservoir Simulation by a Mathematical Model", J. Jap. Ass. Pet. Tech. (Sept., 1972) 245.

2. Stone, H.L.: "Probability Model for Estimating Three-Phase Relative Permeability", J. Pet. Tech. (Feb., 1970) 214.

3. Bjordammen, J. and Coats, K.H.: "Comparison of Alternating-Direction and Successive Overrelaxation Techniques in Simulation of Reservoir Fluid Flow", Soc. Pet. Tech. J. (March, 1969) 47.

APPENDIX



GAS OIL RATIO (SCF/STB)
WATER CUT (%)
PRESSURE (PSIG)
CUMULATIVE OIL PRODUCTION
OIL PRODUCTION RATE
WATER INJECTION RATE
NUMBER OF PRODUCING WELLS
WATER CUT
GAS OIL RATIO
HISTORY MATCH
PREDICTION

APPENDIX IV

Oil-System Correlations

OIL-SYSTEM CORRELATIONS

Correlation curves are made here from the PVT-Data of four fields; Tembungo, West Lutong, Baram and Tukau, for the purpose of determining four properties of primary importance, solution gas oil ratio, bubble-point pressure, formation volume factor, and viscosity of oil, based on the other properties, which are oil gravity, gas gravity, reservoir temperature, and original pressure.

Solution Gas Oil Ratio:

The solubility of natural gas in crude oil (Rs) depends upon the pressure (Pi), the temperature (Tr), and the compositions of the gas (Cg) and the crude oil (ATo). The function may be expressed that;

$$Rs = F0(ATo, Cg, Tr, Pi) \qquad \ldots (1,1)$$

For a paticular gas and crude oil at constant temperature, quantity of solution gas increases with pressure, and at constant pressure the quantity decreases with increasing temperature. Then, the formula (1,1) is expressed by the formula (1,2).

$$Rs = Pi/(Tr + 460) \cdot F1\ (ATo, Cg) \qquad \ldots (1,2)$$

Based on the premise that stock-tank-oil gravity (ro) is a function of the compositions of the gas and the crude oil, the function of solution G.O.R. with temperature, pressure, and composition of natural gas and crude oil is;

$$Rs = Pi / (Tr + 460) \cdot F3 (ro) \qquad \text{... (1,3)}$$

The correlation curve from the formula (1,3) is on Fig. 1. And then, as the second supposition ro = g (Pi, Tr) in the paticular area;

$$Rs = F4 (ro) \qquad \text{... (1,4)}$$

The correlation curve from the formula (1,4) is on Fig. 2, however, the data of West Lutong fit that poorly.

Bubble-Point Pressure:

According to the Standing's correlation, formula (2,1) is the correlation - function that interrelate with the five variables, gas-oil-ratio (Rs), gas gravity (rg), stock-tank-oil gravity (ro), temperature (Tr) and bubble-point pressure (Pb).

$$Pb = 18 Pc \qquad \text{... (2,1)}$$

$$Pc = [(\frac{Rs}{rg})^{0.83} \frac{10^{0.00091Tr}}{10^{0.0125ro}}]$$

Then, $Pb = KPc^{i}$, as a supposition

$$Pb = 11.650\ Pc^{1.180} \qquad \ldots (2,2)$$

The correlation is described by the curve on Fig. 3.

Oil-Formation Volume Factor:

According to Standing's correlation, the correlation-function with oil-formation volume Factor (Bo,b), solution gas-oil ratio (rs), gas gravity (rg), oil gravity (ro), and reservoir temperature is;

$$Bo,b = a + b(Rs(\frac{rg}{ro})^{0.5} + 1.25T)^{c} \qquad \ldots (3,1)$$

Fairly agreeable result was obtained as illustrated on Fig. 4 except for one data of Tembungo field.

Viscosity of Gas-saturated Oil:

Fig. 5 is the correlation curve of the formula (4,1).

$$u = F(Tr,\ P,\ ATo)$$
$$uo = F1\ (Tr,\ O,\ ATo) \qquad \ldots (4,1)$$

where

Tr : Temperature (°F)

P : Pressure (psig)

ATo : Oil-properties

Gravity is used in Fig. 5 for this factor

Fig. 6 is the Chew and Connally's correlation curve, and Fig. 7 is the correlation of the quantities of Chew and Connally's correlation and PVT Data.

Viscosity of gas-saturated oil with temperature, pressure, oil-property and solution gas oil ratio is in combination with Fig. 5, Fig. 6 and Fig. 7.

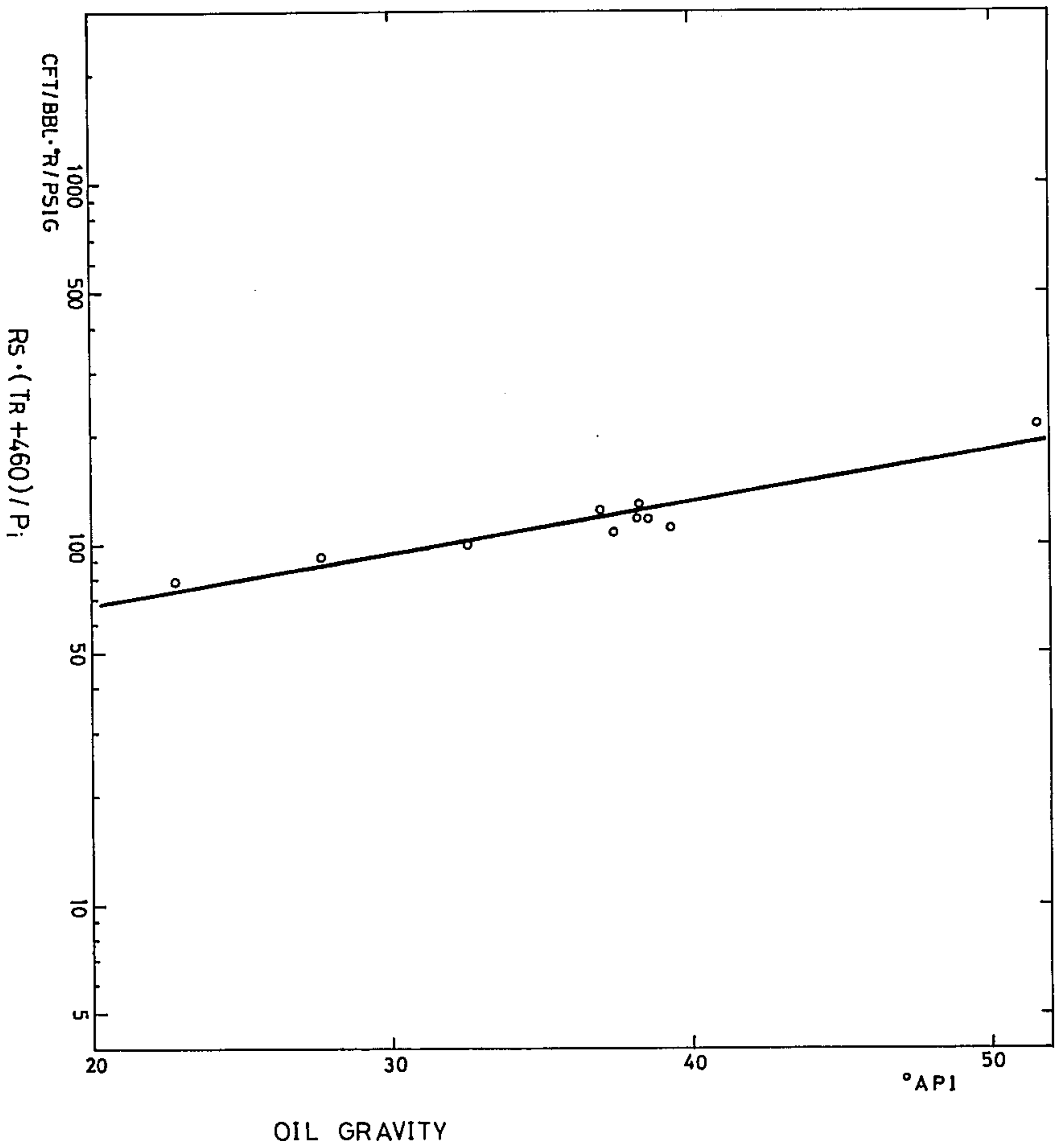


Fig. 1 SOLUTION GAS-OIL RATIO WITH RESERVOIR TEMPERATURE, PRESSURE, AND TANK-OIL GRAVITY

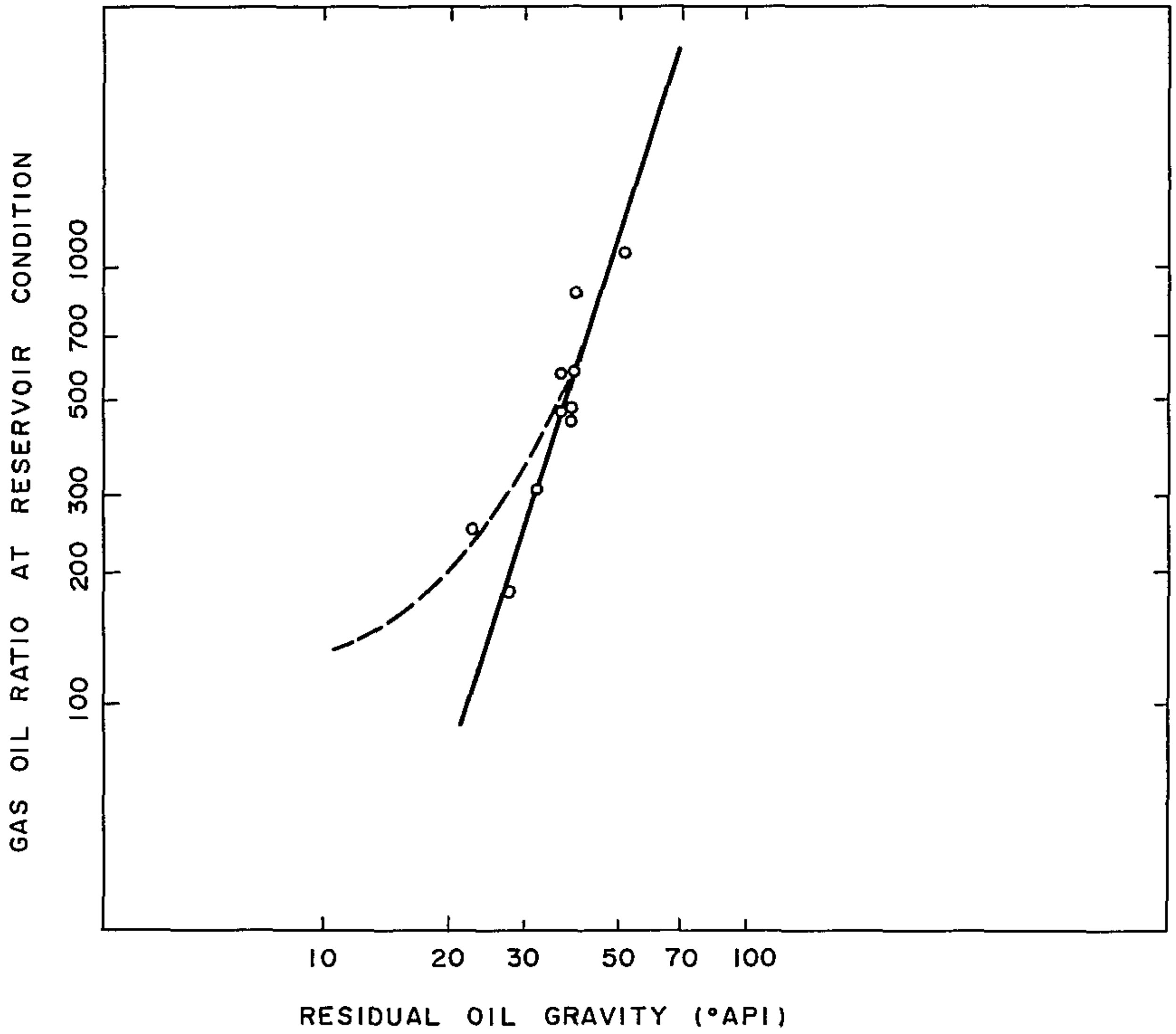


Fig. 2 SOLUTION GAS-OIL RATIO VS.RESIDUAL OIL GRAVITY

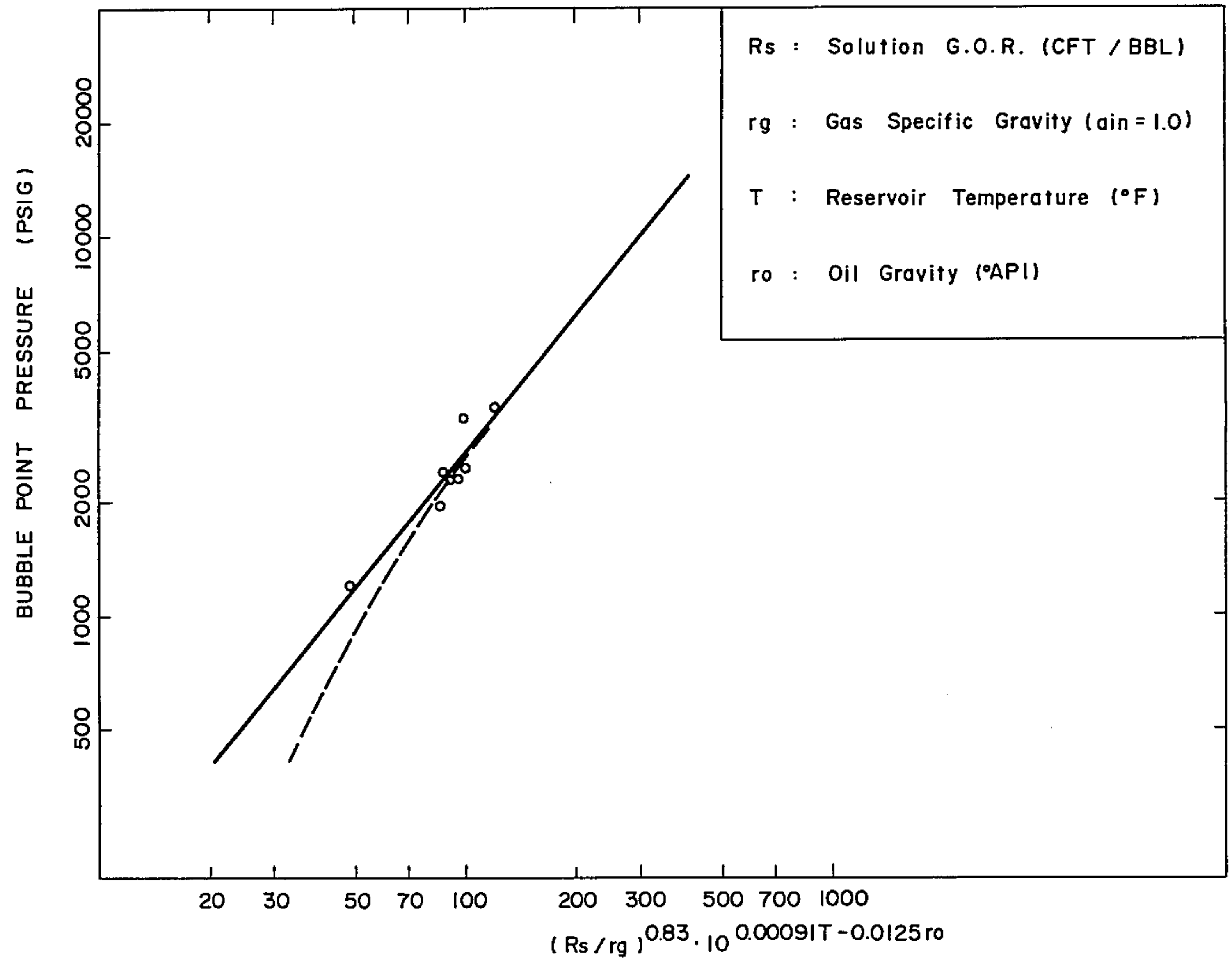


Fig 3 BUBBLE POINT PRESSURE WITH SOLUTION GAS-OIL RATIO, GAS GRAVITY, RESERVOIR TEMPERATURE, AND TANK- OIL GRAVITY

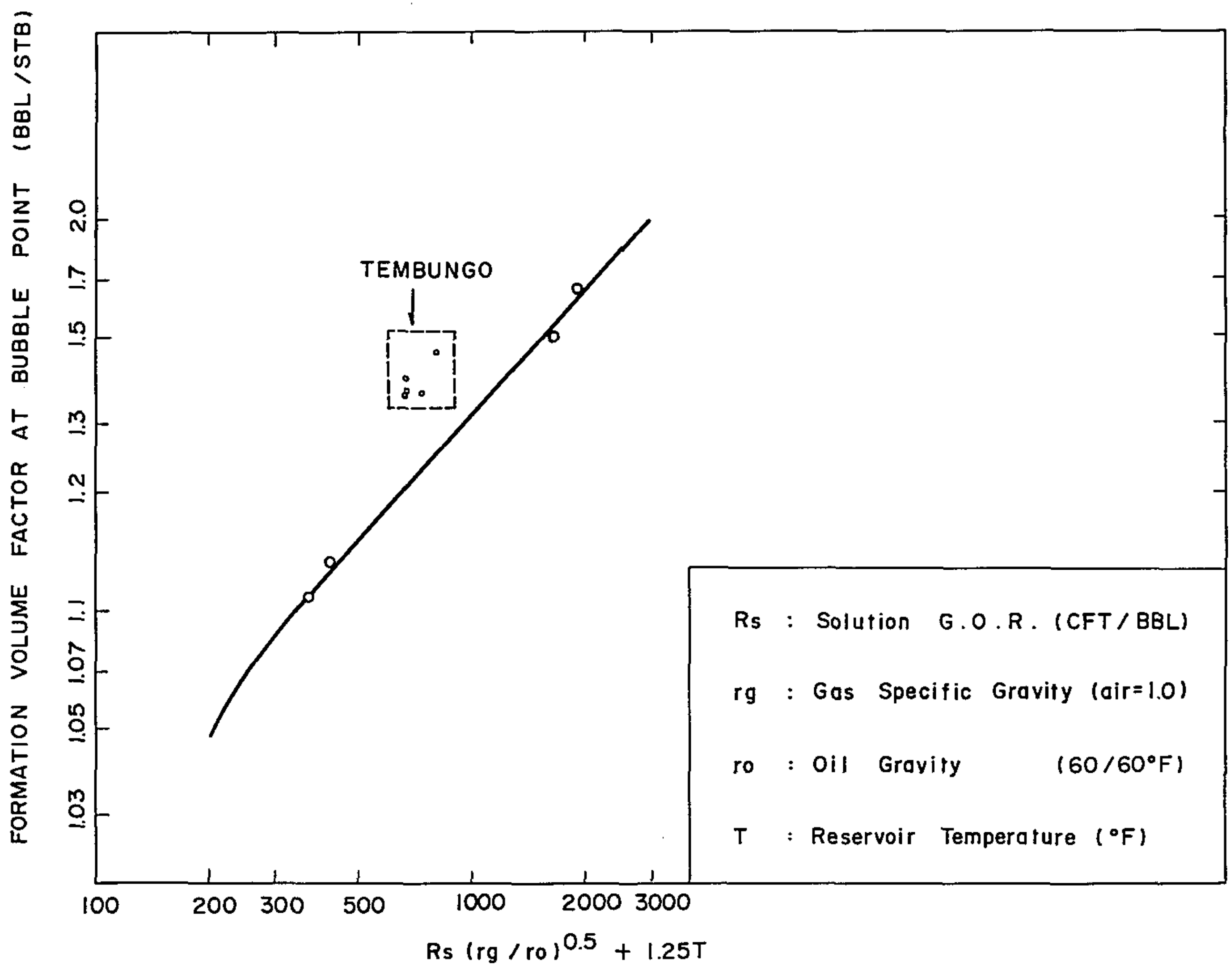


Fig. 4 FORMATION VOLUME FACTOR WITH SOLUTION GAS-OIL RATIO, GAS GRAVITY, TANK-OIL GRAVITY, AND RESERVOIR TEMPERATURE

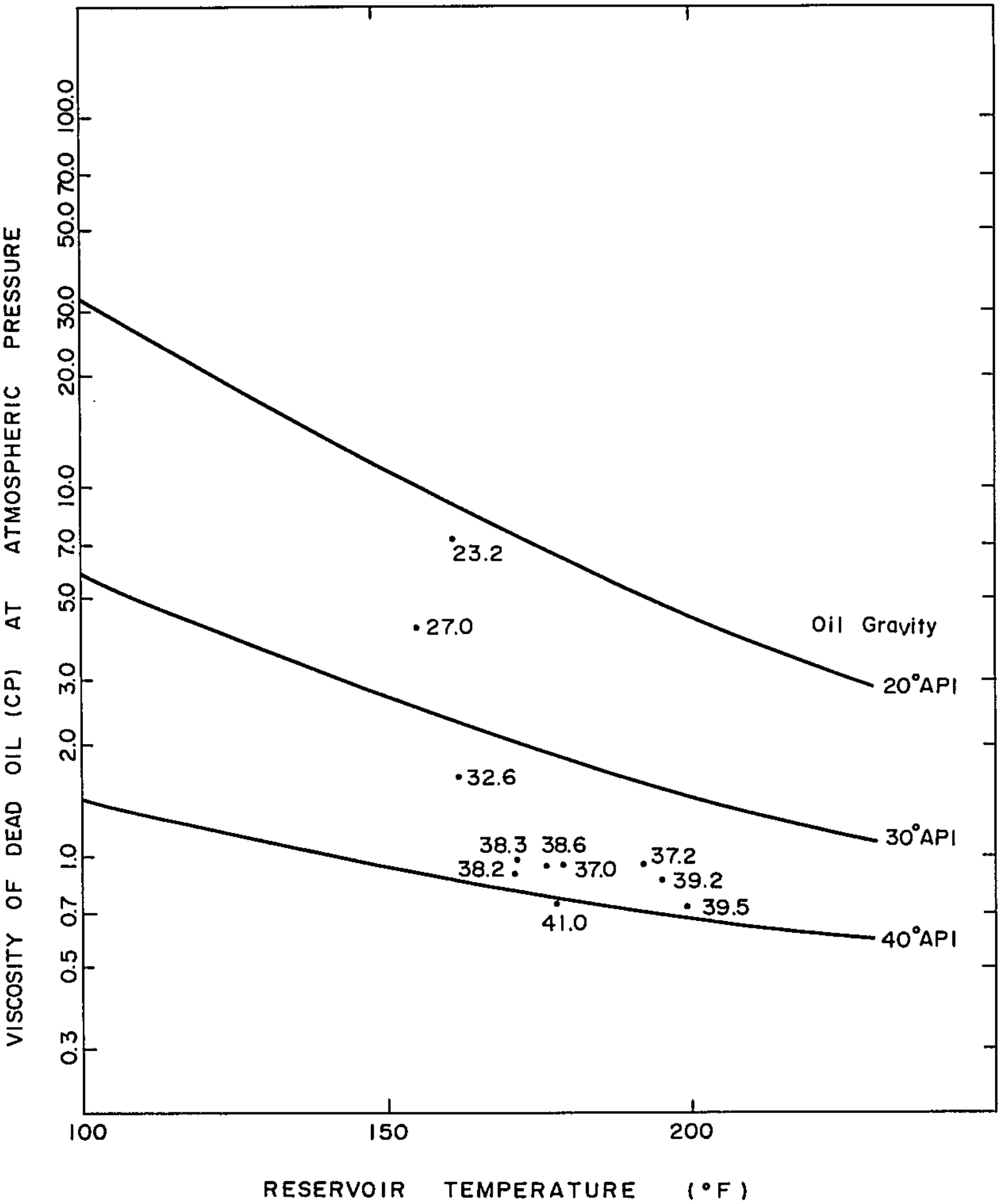


Fig. 5 DEAD-OIL VISCOSITY WITH RESERVOIR TEMPERATURE AND OIL GRAVITY at ATMOSPHERIC PRESSURE

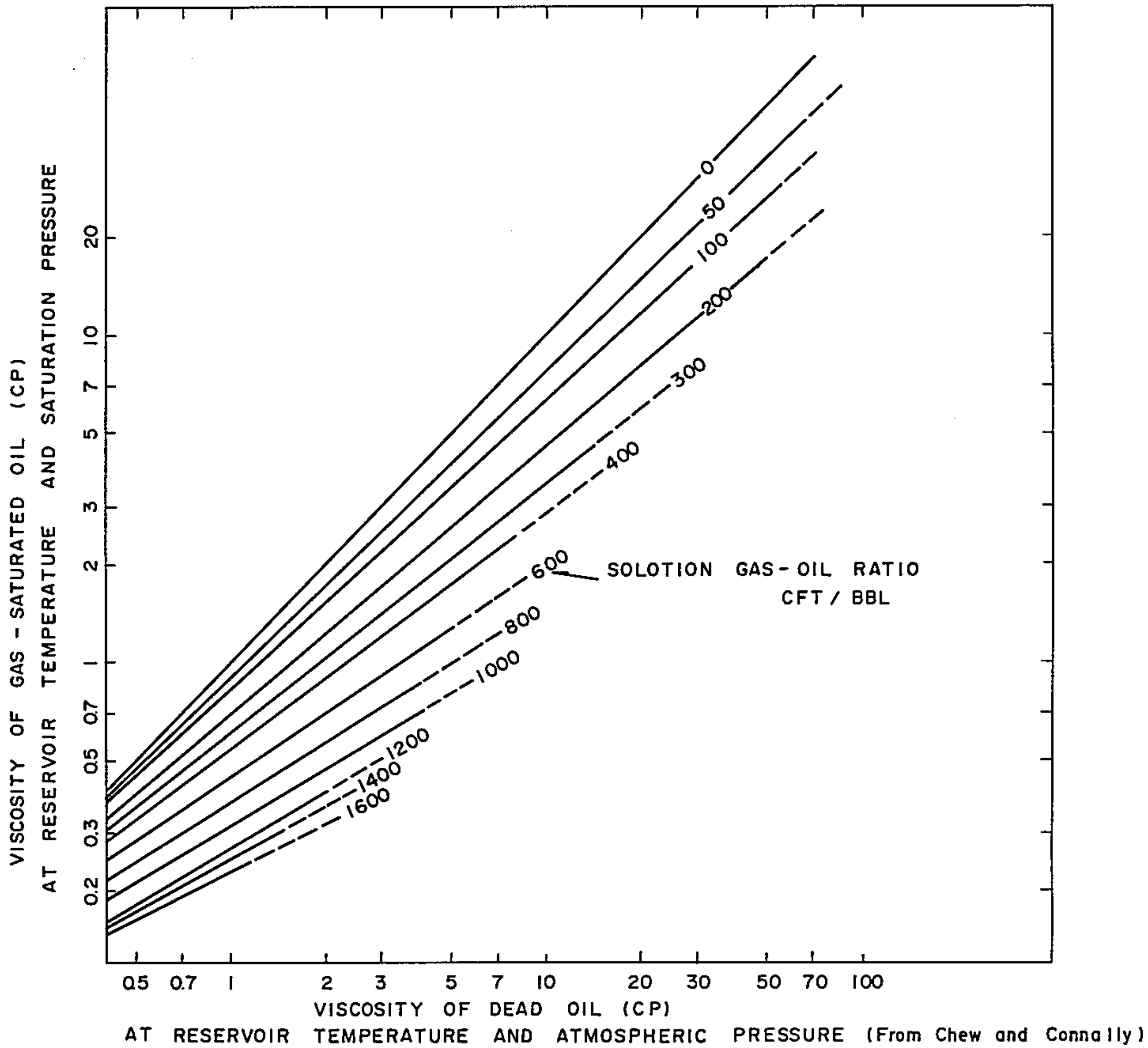


Fig. 6 VISCOSITY OF GAS-SATURATED CRUDE OILS at RESERVOIR TEMPERATURE AND PRESSURE

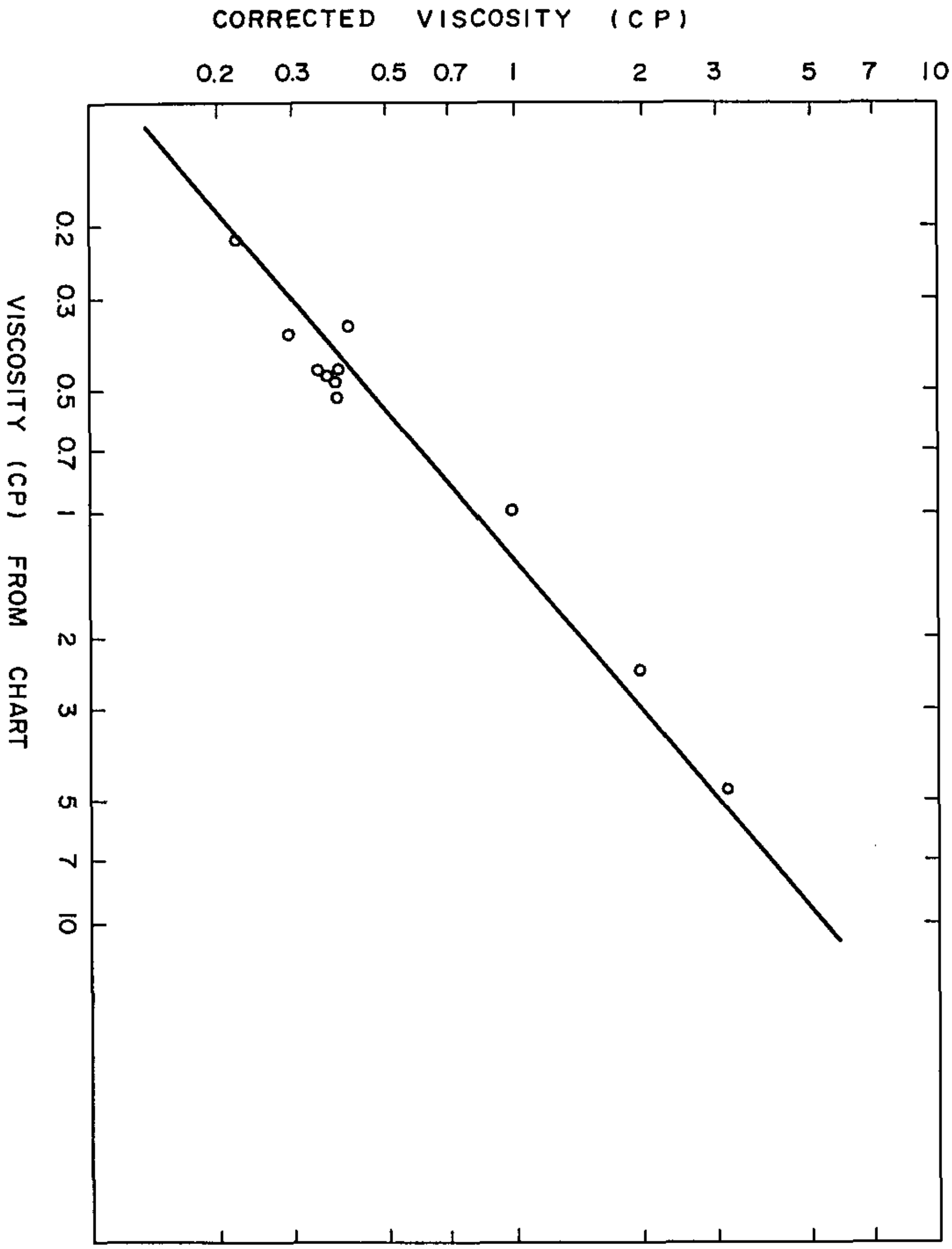


Fig. 7 CORRECTED VISCOSITY VS. PSEUDO VISCOSITY

APPENDIX V

Log Analysis

LOG ANALYSIS

The logs with the scale of 1:200 were digitized every two feet intervals for the quantitative interpretation. The digitized data were processed by computer. Manual analysis was made for the logs with the scale of 1:500.

Porosity:

In calculating porosity, the combination of Density log and Neutron log had primary priority. When either of two was not available, Sonic log was used. But in the shallow non-compacted zone, Sonic log was not used. The effect of the shale on the porosity was adjusted by shale correction. The minimum values of shale contents derived from Density-Neutron crossplot, Gamma ray log, and SP log were adopted as true shale contents. When either of them was considered unsuitable, the log was excluded in calculating shale contents.

Water Saturation:

The calculation of water saturation was done using following formula.

$$\frac{1}{Rt} = \frac{\phi^m S_w{}^n}{a \cdot R_w(1-V_{sh})} + \frac{V_{sh} S_w}{R_{sh}}$$

Where

ϕ : Porosity

S_w : Water saturation

V_{sh} : Shale resistivity

R_w : Water resistivity

m : Cementation factor

n : Saturataon factor

a : Constant in the Archie's formula

Rt : Formation resistivity

Correction for Hydrocarbon Effect:

When the combination of Density log, Neutron log and Microlaterolog are available, the correction for hydrocarbon effect was done. The porosity recorded on log charts is affected by the fluid in the pore space. That is, when Density log and Neutron log record porosities of ϕD and ϕN respectively, following relations exist.

$$\phi D = \phi + Vsh\ \phi Dsh + \phi(1-Sxo)(\phi Dh-1)$$

$$\phi N = \phi + Vsh\ \phi Nsh + \phi(1-Sxo)(\phi Nh-1)(1+2\phi Sxo)$$

$$\frac{1}{Rxo} = \frac{Vsh\ (1-SI)\ Sxo}{Rsh} + \frac{\phi^m\ Sxo^n}{a \cdot Rmf}$$

Where

ϕDsh : Density log response of shale

ϕNsh : Neutron log response of shale

SI : silt index

Rmf : mud filtrate resistivity

Sxo : Residual water saturation

and

$$\phi Nh = 9\rho h\left(\frac{8-5\rho h}{32-5\rho h}\right)$$

$$\phi Dh = 1 + \frac{5}{7}\left[1 - 9\rho h\left(\frac{4-\rho h}{32-5\rho h}\right)\right]$$

Where

ρh : fluid density

From these formula ϕ, Sxo, ρh can be obtained.

Determination of a, m in the Archie's Formula $F = a/\phi^m$.

For the 10 wells shown in Figures, which showed the relations between formation factor and porosity a and m were determined from core analysis. For the fields including these wells, the results were used except two fields, which were Fairy Baram and Sammarang. For the other fields a general formula $F = 0.62/\phi^{2.15}$ for sandstone, or $F = 1/\phi^2$ for limestone was used.

The coefficient a, m and n used for calculation are shown in Table.

Water resistivity:

Water resistivity was determined from SP and the crossplot of true resistivity and porosity for water bearing zones. There was no reliable data derived from water analysis.

When SP derived water resistivity and crossplot derived water resistivity do not coincide, the minimum values in the same field or in the same area were adopted, if possible.

IMPORTANT PARAMETER USED FOR LOG-ANALYSIS

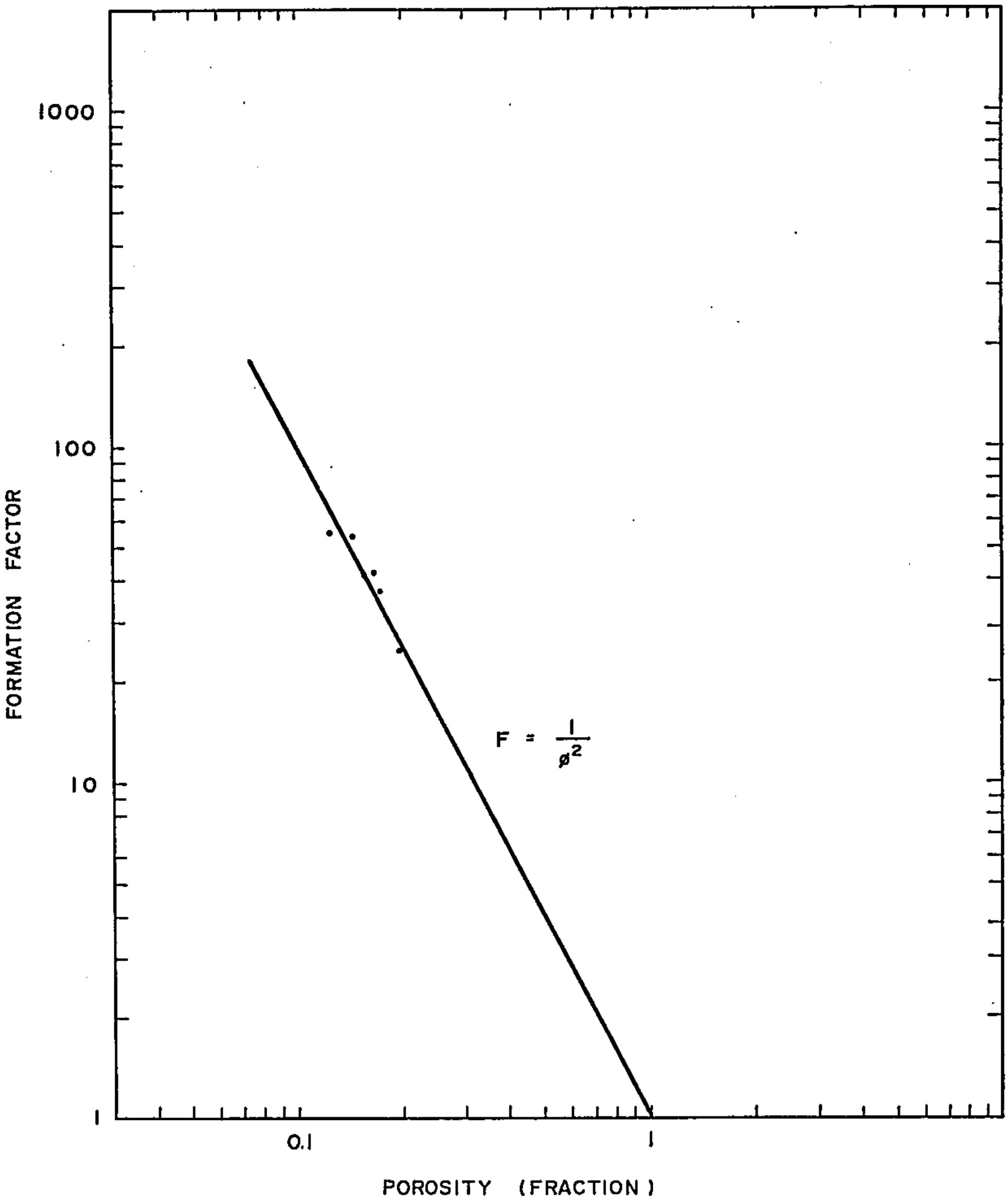
- PENINSULA AREA -

FIELD	CEMENTATION FACTOR (m)	ARCHIE FORMULA'S CONSTANT (a)	SATURATION EXPONENT (n)	WATER RESISTIVITY (Ω-M)
BEKOK	2	1	2	0.22
PULAI	2	1	2	0.2
SELIGI	2	1	2	0.15
TAPIS	1.67	1	2	0.2
SOTONG	1.99	0.86	2.1	0.14
DUYONG	1.87	1	2	0.2
ANDING	2.15	0.62	2	0.296
BELUMUT	2.15	0.62	2	0.17
PETA	2.15	0.62	2	0.21
BESAR	2	1	2	0.15
ANGSI	2.15	0.62	2	0.19
BUJANG	2.15	0.62	2	0.16
SEPAT	2.15	0.62	2	0.20
JERNEH	1.88	1	1.8	0.15
BINTANG	2.15	0.62	2	0.25
PILONG	2	1	2	0.062

IMPORTANT PARAMETER USED FOR LOG-ANALYSIS

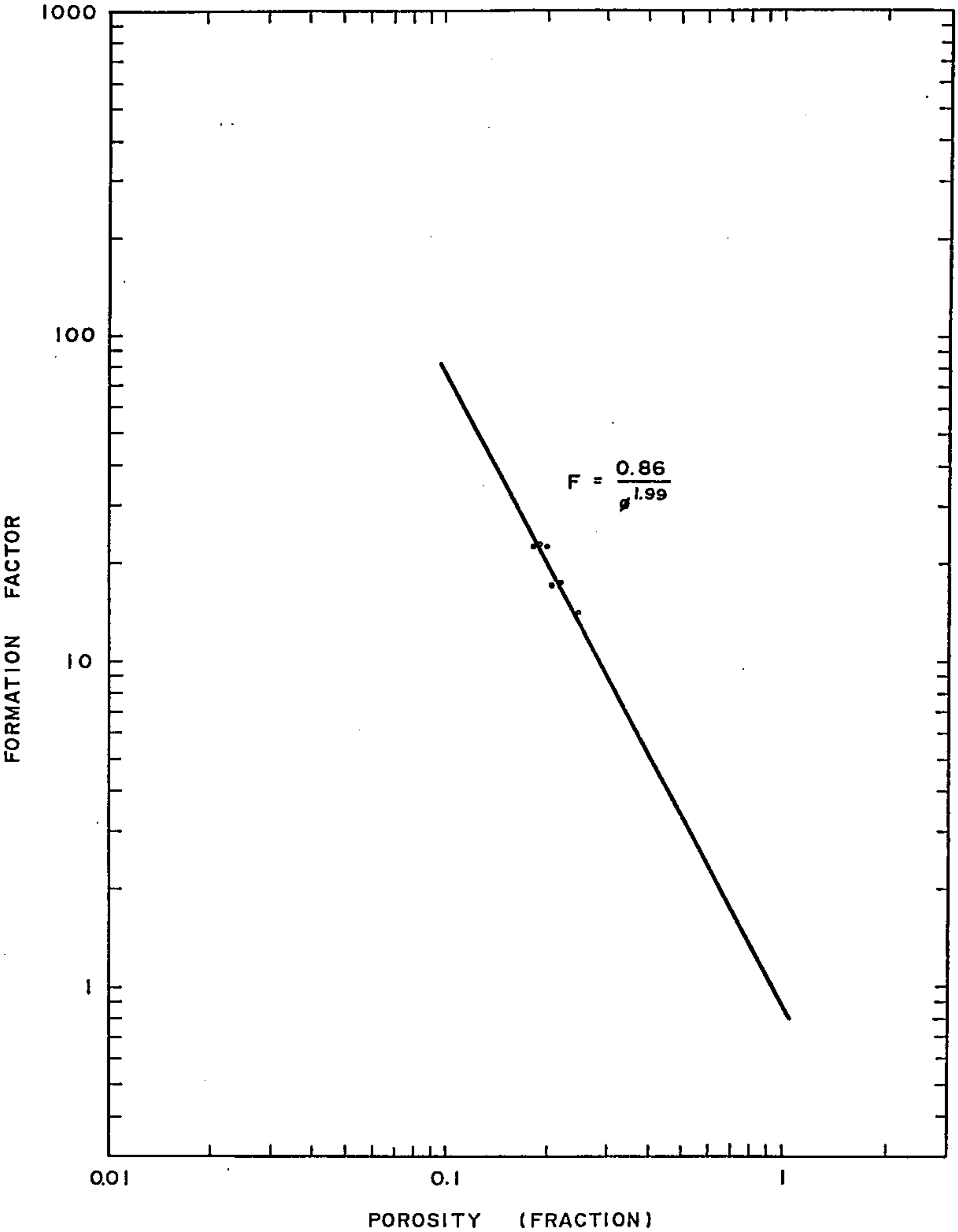
- SABAH AND SARAWAK -

FIELD	CEMENTATION FACTOR (m)	ARCHIE FORMULA'S CONSTANT (a)	SATURATION EXPONENT (n)	WATER RESISTIVITY (Ω-M @ F.T.)
TEMANA	2	1	2	0.15 @ 152°F
SOUTH FURIOUS	1.69	1	2	0.22 @ 155°F
BETTY	2	1	2	0.11 @ 180°F
BOKOR	2.15	0.62	2	0.16 @ 140°F
ERB WEST	2.15	0.62	2	0.13 @ 145°F
ERB SOUTH	2.15	0.62	2	0.3 @ 120°F
ST. JOSEPH	2.15	0.62	2	0.25 @ 150°F
WEST EMERALD	2.15	0.62	2	0.21 @ 135°F
BERYL	1.87	0.7	2	
SIWA	2.15	0.62	2	0.4 @ 120°F
CENTRAL LUCONIA				
B12	1.84	1.04	1.84	0.096@ 240°F
E6	1.84	1.04	1.84	0.23 @ 70°F
E8	1.84	1.04	1.84	0.102@ 148°F
E11	1.84	1.04	1.84	0.096@ 165°F
F6	1.84	1.04	1.84	0.096@ 152°F
F9	2	1	2	0.208@ 170°F
F13	1.84	1.04	0.84	0.25 @ 184°F
F14	1.84	1.04	1.84	0.124@ 148°F
F22	1.84	1.04	1.84	0.2 @ 170°F
F23	1.84	1.04	1.84	0.16 @ 204°F
K4	2	1	2	0.102@ 175°F
M1	1.84	1.04	1.84	0.11 @ 162°F
M3	1.84	1.04	0.84	0.06 @ 203°F
M5	1.84	1.04	1.84	0.06 @ 206°F
BARAM A	1.87	0.7	2	0.135@ 150°F
BARAM B	1.87	0.7	2	0.13 @ 170°F
BAKAU	2.15	0.62	2	0.11 @ 206°F
BARONIA	1.69	1	2.0	0.09 @ 150°F
RAIRLY BARAM	2.15	1	1.49	0.22 @ 70°F
SAMMARANG	1.8	1	1.8	0.111@ 142°F
TEMBUNGO	1.93	1.14	1.93	0.14 @ 150°F
TUKAU	2.15	0.62	2	0.12 @ 140°F
WEST LUTONG	1.84	0.68	2	0.205@ 100°F

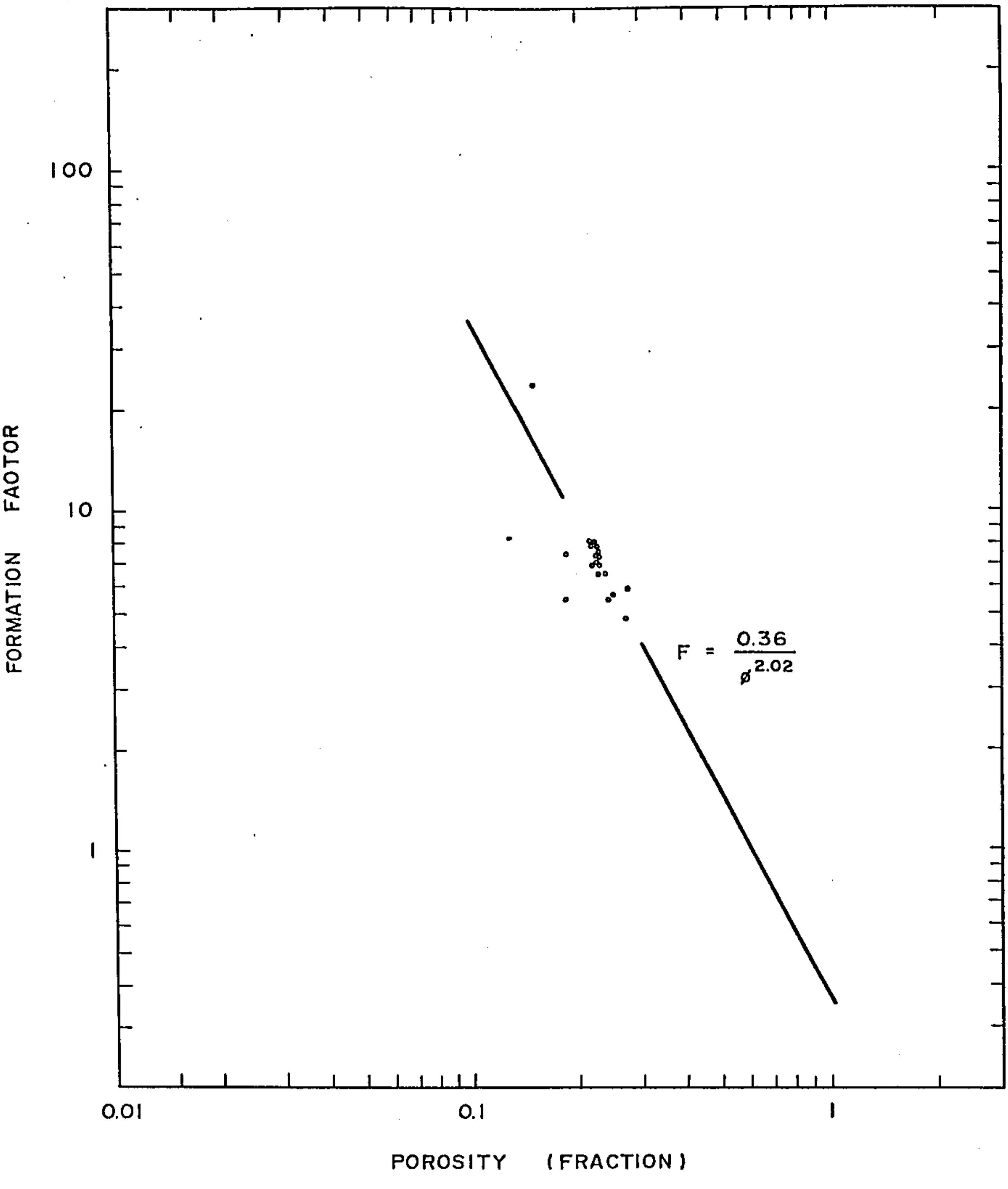


FORMATION FACTOR VS POROSITY PLOT

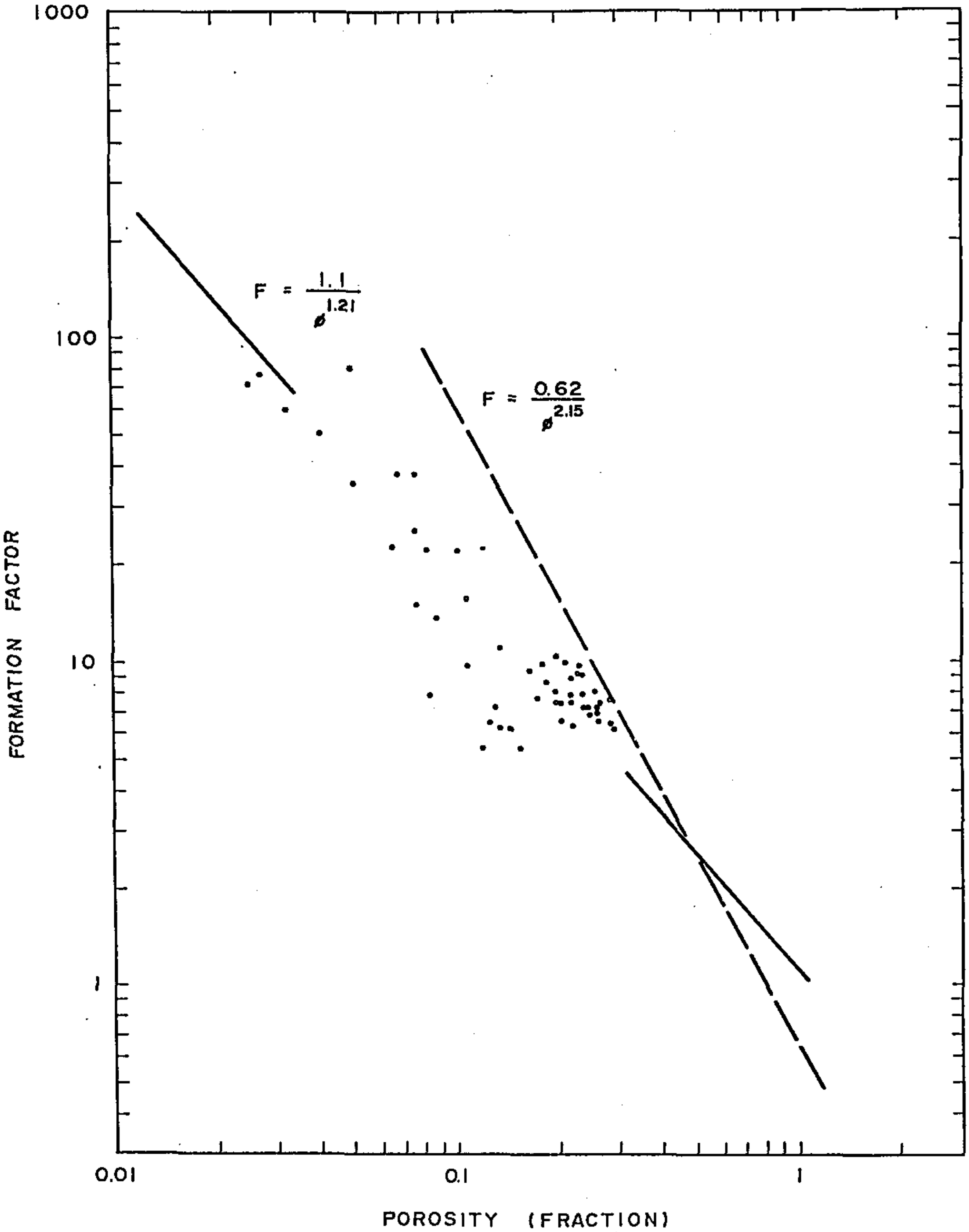
BEKOK 2



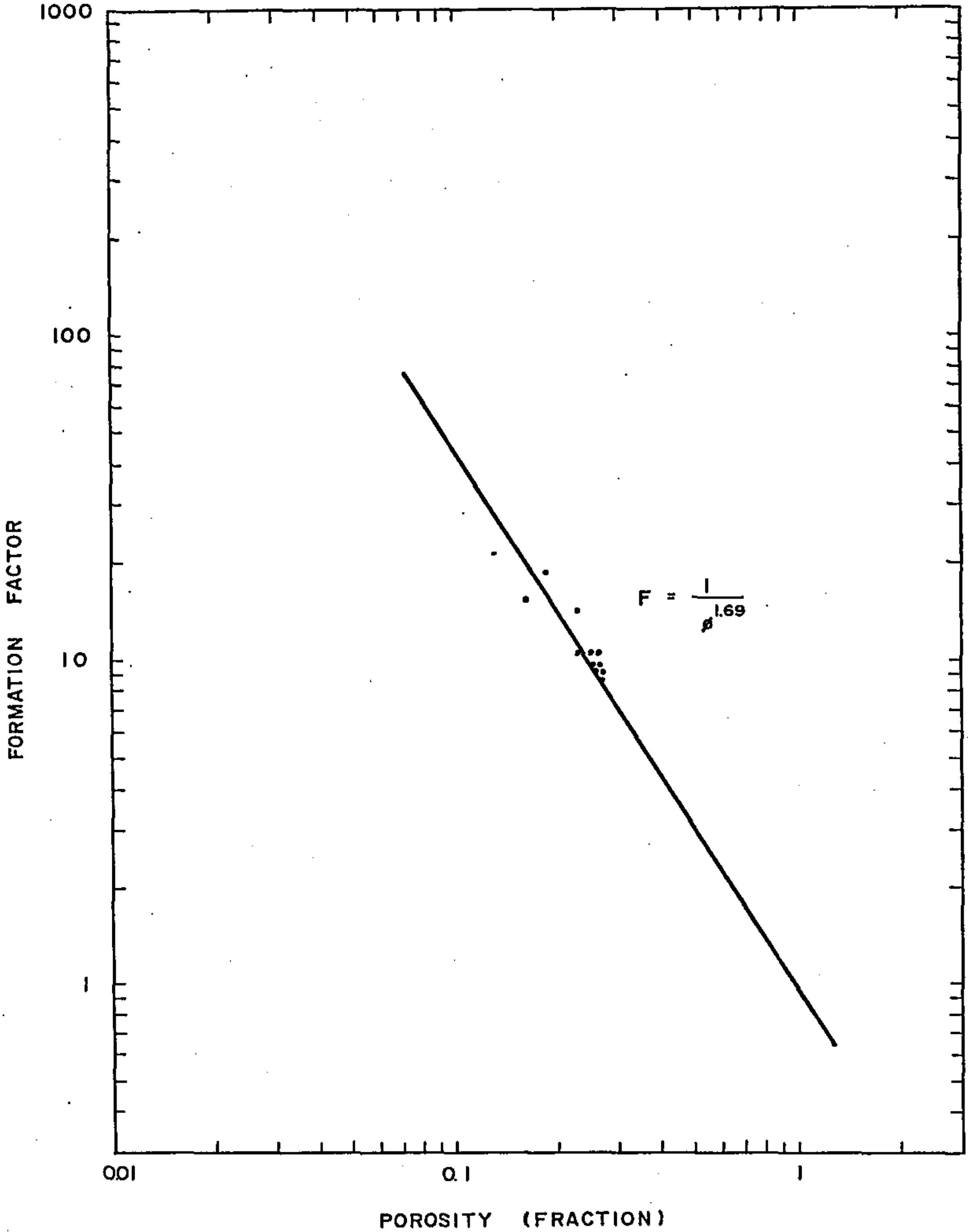
FORMATION FACTOR VS POROSITY PLOT
SOTONG B 3



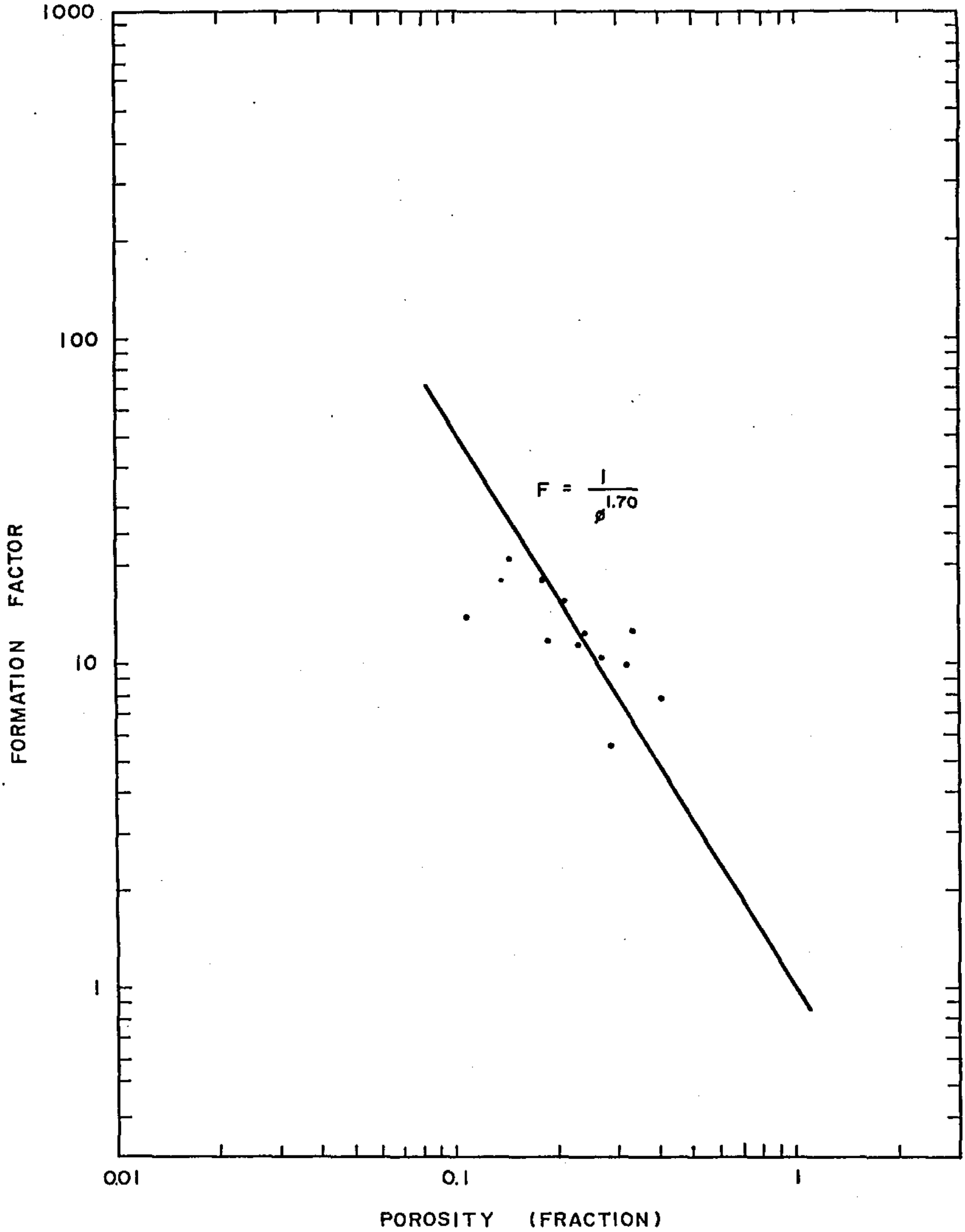
FORMATION FACTOR VS POROSITY PLOT
SAMMARANG IX



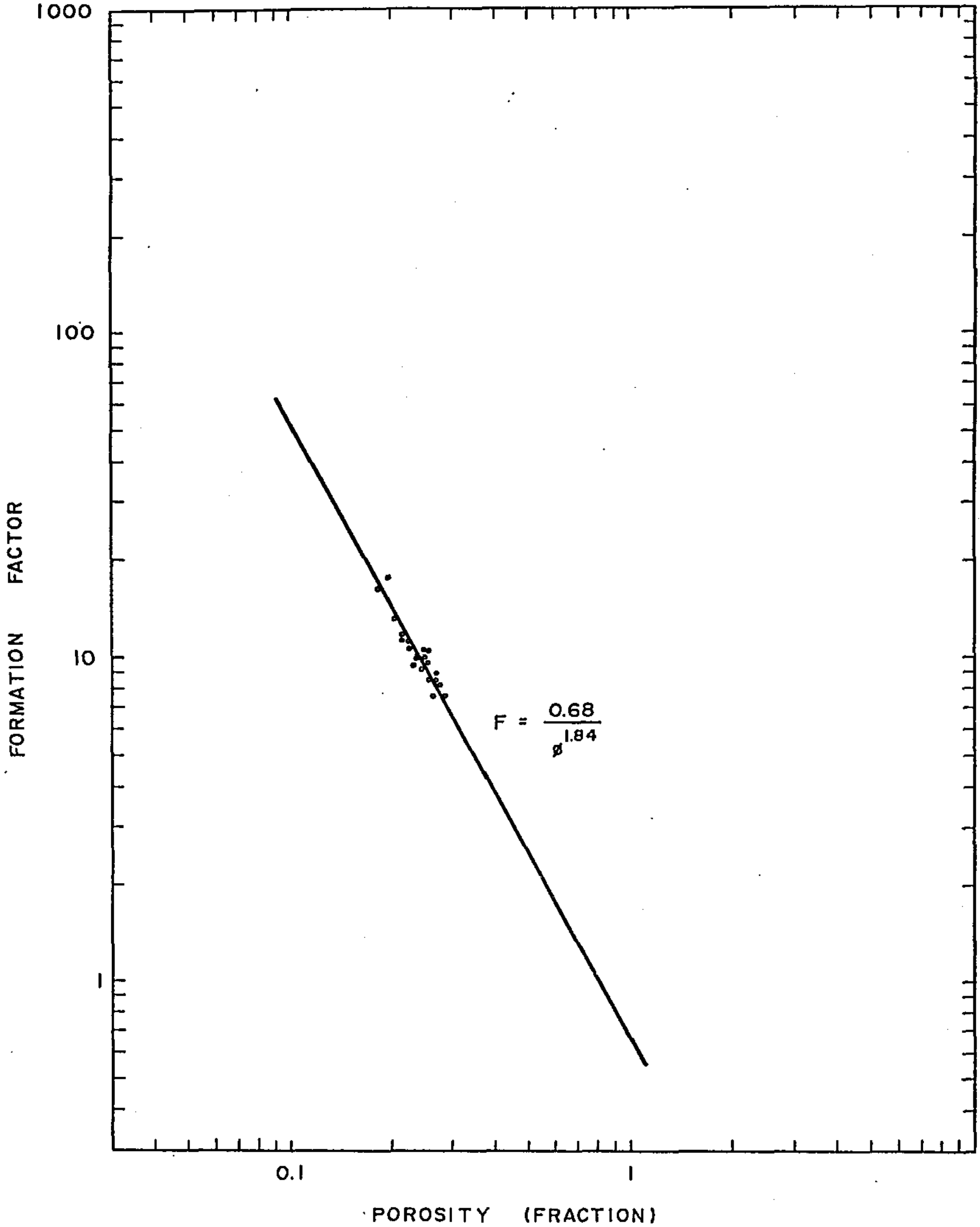
FORMATION FACTOR VS POROSITY PLOT
ERB WEST 4



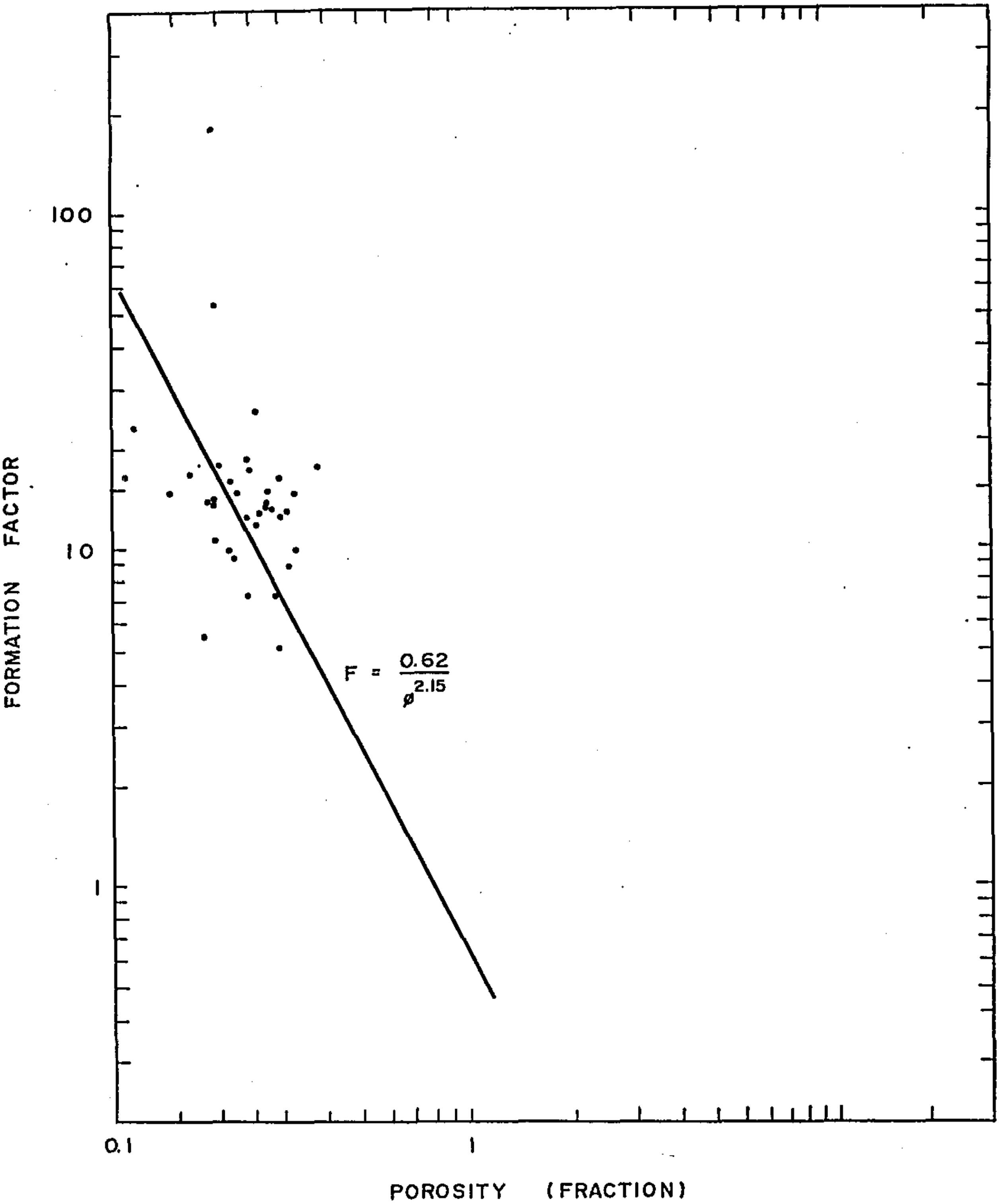
FORMATION FACTOR VS POROSITY PLOT
SOUTH FURIOUS 2X



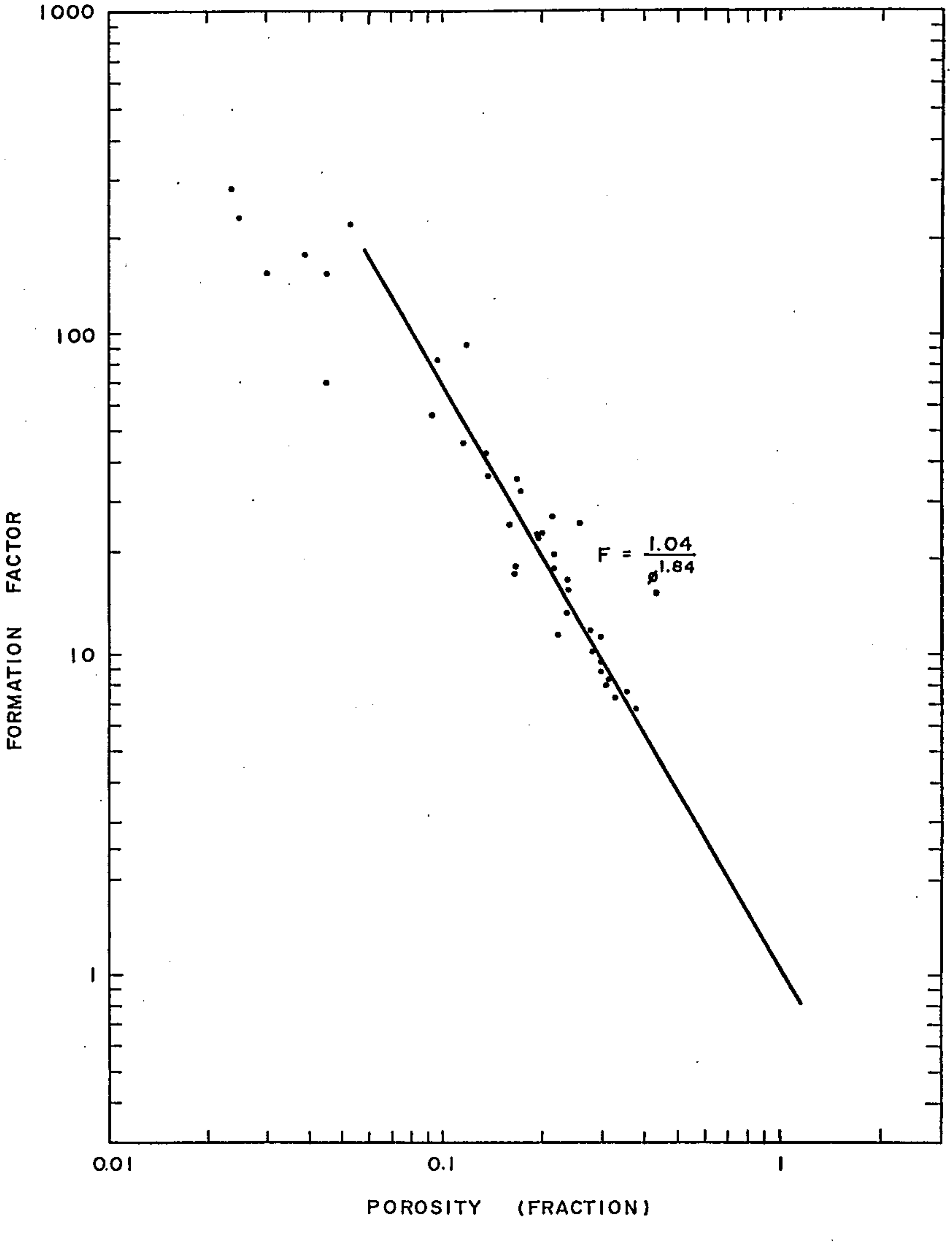
FORMATION FACTOR VS POROSITY PLOT
FAIRLY BARAM 2



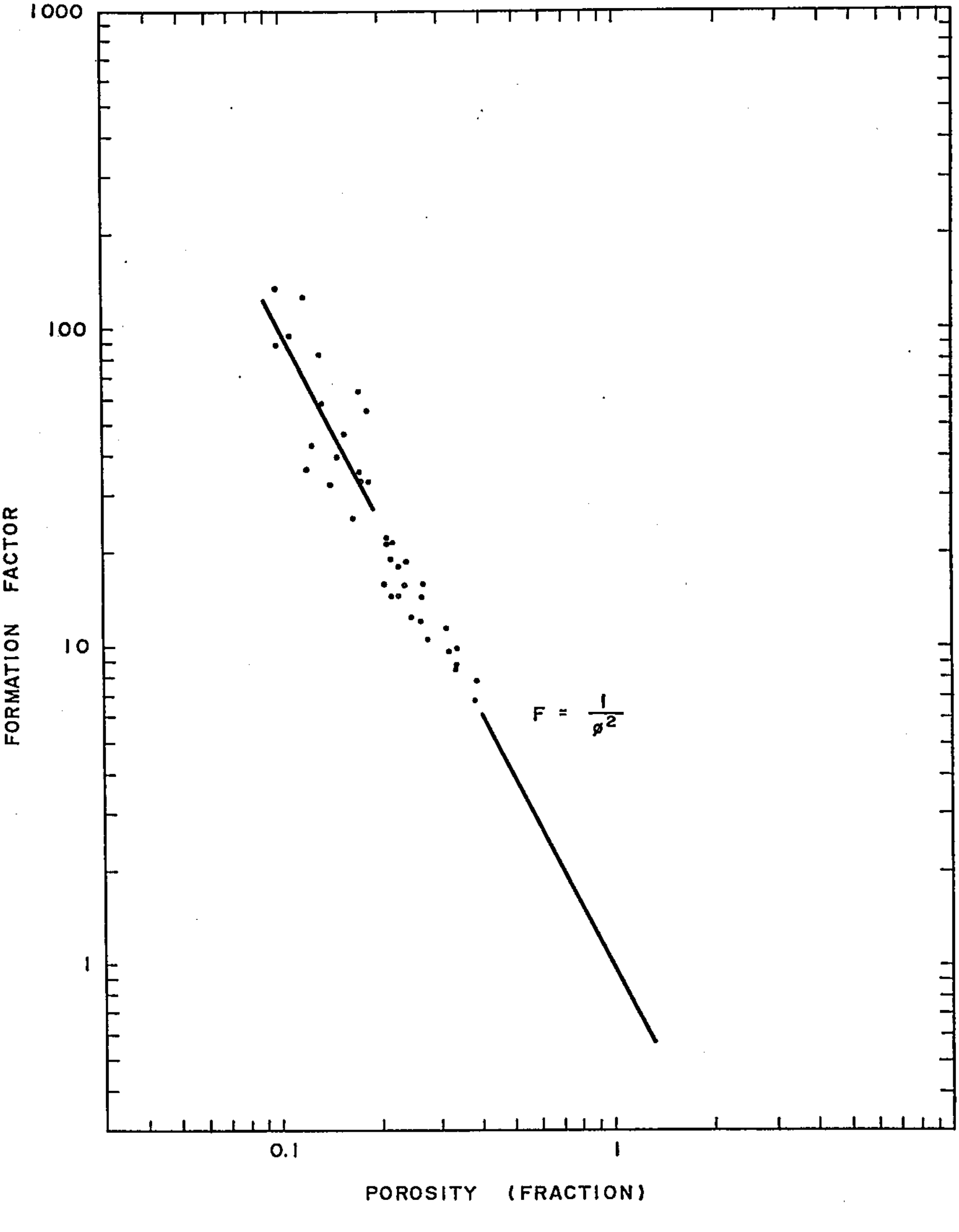
FORMATION FACTOR VS POROSITY PLOT
WEST LUTONG 4



FORMATION FACTOR VS POROSITY PLOT
TUKAU 10



FORMATION FACTOR VS POROSITY PLOT
CENTRAL LUCONIA E8-2



FORMATION FACTOR VS POROSITY PLOT

CENTRAL LUCONIA E 11 – 2