COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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A Review of Current Technology in Several Petroleum Research Laboratories in the United States

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In Cabinet Submission No. 332 approved by Cabinet Decision No. 442(M) of 20th July, 1967, provision was made to continue the Department's policy of sending professional officers of the Bureau of Mineral Resources overseas to study oil exploration methods and techniques currently in use.

The author was selected under this plan to make a 10 week visit to petroleum development and research laboratories in the United States. These organizations were - Marathon Oil Company, Denver, Colorado; Phillips Petroleum Company, Bartlesville, Oklahoma; and three United States Bureau of Mines laboratories respectively located in Laramie, Wyoming; Bartlesville, Oklahoma and Morgantown, West Virginia. In addition, through the courtesy of the Bureau of Mines, one-day visits were arranged to the laboratories of Pan American Petroleum in Tulsa, Continental Petroleum in Ponca City, Oklahoma, and Gulf Oil Corporation in Pittsburgh.

MARATHON OIL COMPANY LABORATORY, DENVER, COLORADO.

The first three days of the visit were spent at the Marathon Petroleum Laboratory. This facility, which is located in the extreme south of Denver, is the main research and production laboratory of Marathon Oil. Although Marathon's head office is located in Findlay, Ohio, their laboratory was built in Denver because of its geographic proximity to most of Marathon's domestic production.

A considerable portion of Marathon's laboratory work, as with most other private companies visited, is directed towards solving their own specific field exploration/production problems. Such tests as permeability (Klinkenberg and liquid) porosity, capillary pressure, relative permeability, water sensitivity, wettability, and occasionally fluid saturation determinations, are all run on occasions, more or less as a routine operation in support of the field operations.

However, efforts are also directed towards a wider research, and one of the most significant developments to result from this for Marathon is the "Maraflood" process. Maraflood may be classified as a miscible phase recovery process. It offers a possible cheap way to recover a considerable portion of the remaining (secondary and tertiary) oil in older depleted reservoirs, thus upgrading recoverable oil reserves.

This process has been in development for a six year period. The process depends on obtaining miscibility with mobility, by an initial invert emulsion detergent-water slug, followed by a polymer-thickened waterflood. Marathon's success with the process has been in keeping costs low in the miscible phase portion of the flood (approximately $3.00 per barrel) by an undisclosed detergent/oil water mixing process which maintains dispersion. This initial phase (0.1 - 0.2 of a pore volume) is able to displace effectively a considerable amount of the previously trapped oil from the smaller interstices of the reservoir, by lowering the interfacial tension; the relatively cheap (10c - 12c/barrel) thickened water which follows is able more effectively to push the displaced oil to a producing well bore.

Field tests are still being conducted in Illinois and Pennsylvania. To date, the former have shown very encouraging results, substantiating the laboratory work. Both five-spot and line drive floods are under way in Illinois; the field test pattern in Pennsylvania (for Penzoil) was not disclosed. The laboratory work which was carried out by Marathon in this process involved two phases. The first was directed towards the physical chemistry of the displacing phase; to find out how to produce a cheap miscible-phase fluid which would stay in suspension, and in low concentrations (5% - 15% of pore volume) effectively sweep the reservoir. Laboratory tests were conducted on both short (3 inch) and long (4 foot) Berea sandstone cores. Early results from this work showed such promise that the field test programme was subsequently planned. Marathon has sufficient faith in the process, that it has proceeded with construction of a detergent plant, and is actively soliciting business from other domestic producers.

The Gamma-Ray Attenuation Porosity Evaluator (GRAPE) is another phase of equipment development in Marathon's research programme. This instrument was developed to measure continuous porosity along the length of whole core samples, without the need for plug analysis. The principle is of measuring density by slowly passing whole core samples through a gamma-ray source. By suitable electronics, the signal is reproduced on a strip chart recorder as porosity (pore space % bulk volume).

The equipment has been found most useful in pinpointing internal anomalies (such as dense inclusions) in core samples. This enabled Marathon to select homogeneous, long Berea sandstone cores for their Maraflood test work, thus minimising the possibility of questionable recoveries caused by some internal core anomalies.

Marathon is continuing to improve this instrument by making it more compact and portable, and will be offering it for sale to the industry.

A third area of research in which this company has been active is in the field of thermal recovery. Both steam and fireflood tests have been carried out in consolidated and disaggregated core material as part of the laboratory programme. Several fireflood tests have been conducted in Marathon's leases to date with limited success. The "Fry" unit in Illinois was a well-engineered test which was a commercial success; other areas (Missouri) did not come up to expectations.

Fireflood tests are conducted in the laboratory by placing crushed core material saturated with oil in a temperature controlled steel sleeve, raising the input temperature to ignition point, and maintaining ignition by injection of the proper amount of oxygen. The effluent gas is collected in large plastic bags, and subsequently analysed by gas chromatography; the oil is collected in suitable glass recepticles and evaluated separately.

Considerable field problems can develop in thermal recovery which can not always be pinpointed in laboratory work. Tests which may appear an economic success in the laboratory may fail in the field. This may result from several reasons; thin pays (high heat losses to the overburden); deep production (high heat losses while injecting in the bore hole); heterogeneous formation (bypassing);insufficient oil saturation (formation unable to support combustion). In addition, if insufficient mineralogical evaluation of the reservoir is available, such minerals as siderite, pyrite and glauconite may become oxidized, partially plugging the formation and reducing the available oxygen to support the flood.

Much of the equipment utilized by Marathon in their laboratory operations has been conceived and developed on the premises. Some of the core analysis equipment in use, notably the relative permeability apparatus was of a very advanced construction. This apparatus was operated on a constant rate principle using an electric Ruska pump as drive. The transfer cells were of high density transparent plastic using a plastic displacement membrane, thus eliminating corrosion problems. The most advanced part of the unit was the effluent fluid measuring device. This consisted of a fine calibrated capillary tubing which passed through an electric eye. The eye is set to distinguish between oil and water as these fluids passed through the tubing, giving a readout on a chart in the relative volumes of each fluid. The equipment could easily be operated by one man, and subsequent to start-up, can run unattended.

The current trend in data handling in Marathon's laboratory is toward complete computerization. Most of their calculations of any complexity are now placed in a large IBM unit, while small Olivetti desk models are becoming common throughout their operations. Plans are continuing to take output data directly from studies such as water floods, chromatograph results etc., and feed them ihto a remote control computer.

UNITED STATES BUREAU OF MINES, LARAMIE, WYOMING.

The town of Laramie, Wyoming is the location of one of the U.S. Bureau of Mines research laboratories. This facility was located in Laramie (population 18,000) because of its central location with respect to the surrounding oil producing areas and with a view also to taking advantage of facilities and expertise of staff at the adjacent University of Wyoming. Laramie is also reasonably near the immense oil shales of Colorado, Wyoming and Utah; a major part of the Bureau research is directed towards economic means of oil extraction from these oil-shale deposits.

The activities of the production research group during the author's visit were as follows :-

(1) A study of the rock matrix properties of the Flat Lake oil field, Montana. Carbonate reservoirs are generally exceedingly heterogeneous in nature, making sound interpretation of their fluid flow characteristics difficult, without adequate petrophysical investigations. A detailed study of the Flat Lake carbonate reservoir, involving porosity, permeability, capillary pressure, pore size distribution and relative permeability was conducted in order to resolve some of its producing characteristics.

(2) A study of electric logs from the same field, correlated with some of the porosity and permeability data. Much of the information was being processed on a computer operated by the University of Wyoming.

(3) A theoretical examination of the effects of a variable free gas saturation on oil recovery during water flooding. This work again was being conducted with the aid of the University computer and will be supplemented at a later date by laboratory testing.

(4) A study involving the determination of the effects of gas diffusion on oil characteristics and saturation pressure in a reservoir. This work is an attempt to explain the variable composition of petroleum in different parts of one reservoir; in effect the investigations are designed to explain saturation anomalies throughout a reservoir in terms of different gas diffusion rates. At present, this work is being carried out on the Rangely oil field of Colorado, but the effects will be studied on other reservoirs in the area if the Rangely field results show them to be warranted.

The routine core analysis equipment in the Laramie laboratory consisted of the standard range of porosity, permeability and fluid saturation apparatus. Porosities are determined by the Boyle law gas expansion method, using a porosimeter constructed by Bureau engineers, while gas permeability is evaluated in an instrument by Ruska. Fluid saturations are rarely determined at the Laramie Centre, this work generally being conducted by commercial laboratories in the area. The apparatus on hand consisted of distillation-extraction equipment using Soxhlet apparatus.

In addition to the above apparatus, some special core analysis equipment is also in use. This comprises equipment to measure mercury injection capillary pressures, waterflood and water-oil relative permeability, imbibition, and water sensitivity. This apparatus was of simple nature, generally requiring two technicians to set up and operate,

The mercury injection apparatus was quite noteworthy in that samples could be tested without the necessary calibration characteristic of the Ruska-type apparatus. Their equipment worked on the principle of using alcohol to force mercury into a sample contained in a closed penetrometer. The penetrometer, a graduated glass container, is immersed in an alcohol medium in the main body of the pump and viewed through a "slit" sight glass. The apparatus also partially eliminates the surface conformance factor characteristic of the Ruska injection equipment in use by our Petroleum Technology laboratory in Canberra.

By far the greatest efforts in research by the Laramie center are directed towards methods of shale-oil extraction. Shale oil reserves represent one of the largest untapped possible sources of petroleum in the world (7 x 10^{12} bbls). Since the majority of these reserves is held by the United States Government, it is apparent why a major effort by the Bureau to find methods of producing this oil is being made.

Research into the extraction of shale oil has taken the following paths :-

(1) Development of "in situ" methods of production. These tests have concentrated on possible methods of creating flow capacity in the deposits, so that some thermal treatment of the strata might enable oil to move to a producing well. This has involved inducing fractures by hydraulic and explosive means, as well as with very high voltage discharges of electricity. In addition, much consideration is being given towards developing a cavern at depth through a nuclear explosion, and subsequent oil production by thermal treatment.

(2) Surface extraction experiments.
These have generally been concerned with strip mining of the shale and retorting it in a large distillation apparatus. These tests are also being used in establishing the economics of "in situ" production in caverns by a nuclear device.

Research in the above field requires a great deal of very specialized equipment. At present the Laramie center is operating a large cylindrical retort (approximately 14' x 5'), gas chromatographs, mass spectrometers, and nuclear magnetic resonance detectors. In addition, several large pieces of apparatus specially designed for producing fractures have been built. There is also a current programme to build a much larger retort to improve on surface retort and "in situ" test data.

Shale-oil production presents a real research challenge to the Laramie center; with the solution of each problem new ones are continually being encountered. This is exemplified in the investigation involving nuclear explosives with subsequent "in situ" retorting. It has been found that on retorting broken oil shale, the action of heat above 650°F on the richer (above 20 gallons per ton) shales produces a consolidation effect; the shale takes on a plastic nature, tending to flow and destroying permeability. This effect, together with the weight of over-burden rubble in a nuclear chimney, would considerably reduce the efficiency of this method of recovery.

Another problem involves the shale itself. The nature of the strata is one of extreme banding with rich zones containing 80 gallons of kerogen per ton interbedded with low grade material less than 20 gallons per ton. This has a marked effect on the efficiency of thermal recovery methods and greatly increases problems with the disposal of waste material.

There is no doubt that with the vast reserves of shale-oil at stake, and the problems involved in its extraction, oil shale research will be the major concern of the Laramie center for some time to come.

PHILLIPS PETROLEUM COMPANY, BARTLESVILLE, OKLAHOMA

Phillips is one of the major American oil companies which owes its origin to the Bartlesville area, where prolific shallow oil production was discovered at the turn of the century. Commencing as a small family concern centered in Bartlesville, the company has grown to a large international organization with diverging interests in numerous countries of the world.

Phillips has its head office and research laboratories in the western suburbs of the town. On this location, the company maintains research facilities for the complete study of petroleum exploration, production, refining and manufacture of petroleum-derived products. A visit to the exploration - production laboratories on this site was arranged on May 20-23.

The core analysis laboratory of the production research group is a large well-equipped establishment containing a full complement of routine and special core analysis facilities. Although this laboratory acts as a service group to the field, test work is usually restricted to "tight" holes and tests of a somewhat confidential nature. A considerable portion of the core analysis requirements of the field personnel is also handled by commercial facilities such as Core Laboratories. However, routine checks on the accuracy of commercial laboratory results are occasionally conducted in this laboratory.

The basic core analysis equipment operated by Phillips consists of a Boyles-law porosimeter; a gas permeameter employing a Fancher type core holder using manometers and gauges for flow capacity measurement; and retort type apparatus for fluid saturation determinations. This equipment was all designed for conventional plug (cylindrical, 1-inch diameter) analysis. However, provision has also been made to analyse sidewall samples in smaller retorts. Whole core analysis is not carried out at Phillips; this work in the past has been farmed out to commercial laboratories when required.

A wide range of equipment for special core analysis is also maintained in this laboratory. This consists of gas-oil and water-oil relative permeability, water flood and water sensitivity apparatus, wettability, resistivity, capillary pressure and density measuring equipment. The relative permeability apparatus consists of a flexible rubber sleeved Hassler-cell with calibrated gas and oil measuring (glass) apparatus. Gas (Helium) is used to displace oil by the unsteady state method from a sample contained in the Hassler-cell; the permeability of each phase is calculated at a number of points throughout the test.

Calculations are carried out on the central office computer, using the Johnson, Bossler and Nauman calculation procedures. Some dissatisfaction was expressed by Phillips concerning the present, generally used, methods of evaluating relative permeability, and they were actively examining new approaches to improve results. I met with similar comments in the other laboratories visited during this tour.

Capillary pressure tests were conducted by two methods. The porous diaphram method was used in cases of samples with good flow capacity; a centrifuge was employed for less permeable samples requiring high displacement pressures to obtain residual saturations.

The geochemical group represents another very active part of Phillips research investigations. The majority of the work in this section is devoted to source rock study and identification. However, the study of clays and clay minerals (by X-ray diffraction and other tests) is also carried on.

Although this work was of a somewhat confidential nature, it was disclosed that Phillips has approached the study of source rocks and possible zones of petroleum generation in a completely new manner. Rather than investigating older producing areas, for their studies they have chosen locations which have not been investigated for source rock studies previously. This has been of considerable assistance in their exploration drilling programme, and has enabled them to develop a number of original ideas for their exploration work.

A third group visited at Phillips was a section designated "Chemical and Characterization". The staff of this group act as advisors on a service basis to any of the sections throughout Phillips research laboratories. It is their duty to analyse, identify and test various compounds which are given to them for study. They have been invaluable to the geochemistry group through their assistance in analysing of unknown substances for the source rock study.

The equipment used by this group included chromatographs, infra-red analysis, mass spectrometers, nuclear magnetic resonance equipment and fractional distillation (Podbielniak) apparatus, as well as the standard test apparatus found in most chemical laboratories. It is shortly proposed to direct the output of their chromatographs into a central computer, to save time.

One of the most diversified pieces of equipment in use by this section was a televiewing electron microscope. This unit has a resolution of 200 angstroms and can magnify up to 16000 times. Because of its ability to retain everything in focus, giving the operator an in-depth picture of his investigation, this apparatus has been widely acclaimed in research centres in the United States. Phillips has found a very broad use for this unit in studying textiles and fibres, plastics, metallic coatings, as well as various minerals and rocks.

In the latter application, this microscope has been most useful in upgrading the study of clays in a rock matrix. It is possible to "zoom" in a particular area of a sample to study the relationship between the clays, grains and pore openings, all of which are in focus. Permanent visual evidence at any point of magnification can be obtained through photography by directing the televiewed image through a camera.

This equipment was designed and built by Cambridge Instruments of Cambridge, England, and costs approximately $80,000 with all the accessory equipment. Phillips contends that the cost has been written off solely on the work which they have accomplished in their textile field.

UNITED STATES BUREAU OF MINES, BARTLESVILLE, OKLAHOMA

The Bartlesville station of the U.S. Bureau of Mines was constructed in 1918, as a result of an Act of Congress three years previously. This Act gave the fledgling Bureau of Mines authority to set up seventeen experimental stations, and nine safety stations throughout the United States, the Bartlesville laboratory being the only location devoted solely to petroleum investigations.

The establishment of this station in the small town of Bartlesville came as a result of some good public relations by its citizens, coupled with a desire by the government to set up operations in an active part of the mid-continent. Conservation and good production practices were almost unknown in this area in 1918, and it was to this end that its staff applied themselves. Letters were sent out to prominent oil men in the surrounding areas outlining plans for the new station, and inviting research suggestions. The first paper published by the new station was titled "Methods of increasing recovery from oil sands" and was widely acclaimed.

In the 50 years since its inception, the Bartlesville station has vastly expanded its facilities and range of research. This has greatly aided the oil industry and country at large through conservation, and the upgrading of reserves through improved production practices. It has never been the policy of the Bartlesville station to force their opinions and results of their work on the producers. However, many of this station's studies have been gratefully accepted by the industry, as a considerable help in the quest for increasing reserves.

The following is a summary of the activities witnessed by the author during a four-week visit to this station:

(1) Study of wetting properties, interfacial tension, additives and their effect on waterflood performance of reservoir core samples.

This work, which has been in progress for about one year, was initiated by using outcrop core samples. The natural wetting properties of these samples were determined by a test especially devised by the Bureau. It involves measuring the capillary pressure of water displacing oil and oil displacing water from core samples in a centrifuge. A degree of wetting (a maximum of +1 for water wet; -1 for oil wet). is evaluated in each sample by calculating the ratio of the areas under each capillary curve.

Subsequent to this, the interfacial tension of various brine/ oil systems used was measured in a modified pendant drop apparatus, whereupon samples are flooded to residual oil saturation. The object of the latter part of the test is to evaluate the effects of rock wetting properties and interfacial tensions of the fluids used, on oil recovery during water flooding.

Another test series has been commenced following the above procedure, excepting the following: fresh, preserved cores are now being used together with native oil and brine. In addition, flooding waters are being treated with various additives to alter the oil-water interfacial tension. The object of these tests is to discover the most efficient means of improving oil recovery by using various additives in the flooding water.

(2) The use of monopropellants in improving permeability of reservoir rocks.

The improvement of permeability in reservoir rocks has long been a subject of intensive study by researchers. A literature survey on this topic by the Bureau revealed numerous approaches to the subject. Of particular interest to them was a test by the University of California, in which permeability had been improved by heating core samples in a high temperature furnace.

Following this lead, the Bureau solicited rocket fuel manufacturers in an attempt to find a high temperature fuel which could be burned in the interconnected pore space of a rock, and possibly increase permeability. This presented some problems, because of the confidential nature of rocket research, also because most fuels were unsuitable for this specific purpose.

Eventually, a satisfactory fluid (hydrazine hydrate) was located. This fuel burned at a high temperature, and did not require the addition of oxygen to be self sustaining.

However, success with the method was somewhat mediocre; it was found that certain physical conditions were required in the cores before ignition and permeability improvement could be effected. The best condition for burning was found in samples with low permeability, and with porosity greater than 20 percent. Some samples with these characteristics gave up to a tenfold increase in premeability; others of a similar nature showed little improvement.

The success of the method appears largely dependent on the development of cleavage fractures in the silica grains of the samples, as well as dehydration of the clays and the binding cements. In general, it was found that failures were caused by incomplete burning due to poor saturation with the fuel.

The hydrazine hydrate used in these tests was found to have an interesting side effect on some core samples. Upon leaving cores saturated with this monopropellant for a length of time before burning, a disaggregation of the core was noted to occur. This was further studied and found to be the result of an undetermined chemical reaction between the monopropellant and the cementing material. Research in this field using additional types of core samples and different fuels is being continued.

(3) Project Gasbuggy is a joint effort by El Paso Natural Gas, United States Atomic Energy Commission, Lawrence Radiation Laboratory, and the United States Bureau of Mines to explode a nuclear device in the "tight" Pictured Cliffs sandstone of the San Juan Basin, New Mexico; the object being to increase considerably permeability and radius of drainage of the wellbore through production of a large cavern above the detonation point. Two engineers, Mr. C. Atkinson and Mr. D. Ward were the Bartlesville representatives for the Bureau of Mines, and were responsible for the main reservoir engineering of the project.

The actual laboratory work conducted by the Bureau in regard to this test was rather small. Some studies of radioactivity hazards were carried out prior to the shot, in addition to some rather extensive physical testing of porosity and permeability of core samples from the test hole area. However, most of the study was involved with engineering calculations from the previously known data about the reservoir.

A discussion with the two engineers from the Bureau involved with the project was held during the visit to Bartlesville, and the various aspects of the project to date were reviewed. At that time, the re-entry hole to the cavern had just been drilled, so that some communication with the top of the cavern was apparent; radio-activity had been encountered with a build up in pressure in the re-entry hole. Although the pressure buildup appeared to be slow, it was suggested that this was probably due to poor communication between the partially completed re-entry bore and the main cavern.

The use of nuclear stimulation in other petroleum reservoir stimulation projects throughout the Rocky Mountain area were also discussed. It was obvious that the Bureau of Mines engineers did not share the unguarded enthusiasm for some of the other projects in the area as did the companies involved.

A short discussion on the possible application of nuclear stimulation in the Mereenie field followed. Mr. Atkinson suggested that the total thickness of the oil column at Mereenie might not be sufficient for the use of a nuclear explosive, and that the possibility of both water and gas coning could result. In addition, he was somewhat more sceptical of the radioactivity problem in oil than its effects in gas. Questioned as to the applicability of nuclear explosives to the "Stairway" and "Upper Pacoota" gas sands at Mereenie, he considered that with distance to markets and other factors, such a treatment was uneconomic at the present time.

(4) Geochemistry. The use of radioactive materials in the course of investigations is becoming an increasingly important part of the Bureau of Mines laboratory operations, This has taken the form of tracers in waterflood tests, and neutron bombardment of petroleum samples to aid identification of mineral constituents in oils.

Another recent development in the use of radioactivity has been in the field of geochemistry. This has involved a gamma-ray producing cobalt - 60 generator, simulated sedimentary material, and a long chain fatty acid. The programme has involved the irradiation of the acid (behenic acid) by itself, then irradiation of the acid after it becomes attached to a surface (pure silica sand, bentonite and calcite).

A sample of the behenic acid attached to one of the above surfaces is left in the generator for 168 hours and exposed to gamma radiation. During this period, the products from the sample and container are drawn off into an evacuated steel cell, then analysed by gas-liquid chromatography on completion of the test.

Tests were performed in this fashion using three simulated sediments (sandstone, clay and limestone) as the bonding surface for the behenic acid. The product analysis in each case revealed hydrocarbons ranging from methane to pentane, with substantial amounts of hydrogen and carbon dioxide.

This work presents another interesting approach to the problem of petroleum generation. The study does not attempt to refute other theories of petroleum generation, but it does help to explain how the subsurface environment can influence the generation and migration of petroleum from some source rock to a reservoir. The radioactivity involved in this process may have various sources, one being the natural radiation of a shale, active over considerable geologic time. Other sources might be from some adjacent intrusive igneous body.

Future tests on this work will be continued using other types of bonding surfaces for the behenic acid, such as kaolinite. Natural shales may also be used at a later date provided sufficient accurate data on surface area measurements and any extraneous organic content can be identified before testing.

(5) The mobility of multi-phase fluids. The increasing importance of natural gas in the energy market has lead to recent studies to determine the period that gas may be recovered from a reservoir at some required rate. It has become as important a factor to know the amount of gas which can be delivered at this rate, as it is to know the availability of the recoverable reserves. When pressure decline causes retrograde condensation of the liquid ends to occur around a well bore, it is most important to know what effect this resultant restricted flow will have on deliverability of the gas to a pipeline.

Research towards this end being carried out by the Bureau of Mines in Bartlesville involves a study and evaluation of the effect on gas mobility in core samples of varying pressure, liquid/vapour saturation, flow velocity, lithology and length-to-diameter ratio.

The apparatus in use accomodates a one-inch diameter core sample mounted with epoxy resin in a steel sleeve. The core ends are sealed with "O" rings and bolted in place. Upon establishing a gas saturation in the core sample, a predetermined gas/liquid injection rate is effected by constant rate pumps. Under conditions of steady state flow, production is measured from the effluent at a constant differential pressure, and the flow characteristics of the two phases are monitored.

A number of tests have shown that relative mobility and the liquid-vapour volume relationship depend on pressure, saturation, and to a lesser extent on velocity. For each porous medium and fluid tested, there appears to be a minimum saturation essential to two-phase flow. It has been found that high flow velocities have only limited effect on saturation in the velocity range (above 0.30 cms/sec) studied.

(6) Thermal recovery. The use of thermal recovery methods in the United States during the past few years has been broadened considerably. Steam injection and fireflooding have found considerable scope in the production of high viscosity oil. Both production mechanisms are currently being extensively studied in most petroleum engineering laboratories, especially in difficult production areas associated with very high gravity oil.

The Bartlesville station has recently commenced a study in which they have elected to evaluate the potential of steam drive in an oil reservoir, measuring the oil expelled in a liquid and vapour state, as well as the steam, to determine the displacement efficiency of the system.

The theory in this work is that steam, on contacting crude oil, vapourizes a fraction of the lighter ends. These are transported to the flood front in a vapour state and condense in the cooler forward zone with the steam. It is assumed that on building up a bank of this re-condensed oil, a normal waterflood displacement occurs towards the producing well. This theory will be tested on both low and high gravity oils.

The equipment to be used in these tests is comprised of a steel, sand pack tube 5 feet in length, which is kept at a controlled heat in a constant temperature bath; an electric (arc welder) heater to convert distilled water to steam; and a refrigerated condensing system for re-condensing the vapour effluents. The sand pack tube is mounted on a bearing, allowing rotation of the tube to minimize gravity drainage during testing. A periscope eye-piece allows the operator to control the flow by back-pressure, so that oil is produced through a lower port, and vapourized petroleum and steam through an upper port.

The initial task of the project will be an attempt to corroborate theoretical data developed by other investigators in which various gravity oils are subjected to a 100% quality steam drive through core samples. Comparisons will also be made in the relative efficiency of this displacement mechanism with other oil recovery methods such as cold and hot water injection.

(7) Vapourization by gas cycling. The object of this project is to develop new methods, or improve on presently accepted methods of oil recovery, by high pressure gas cycling. The effect of oil type, reservoir pressure and reservoir temperature is being studied in a rotating model oil reservoir during cycling. From these data, a family of curves will be developed which will show these variable effects on recovery. To date, these tests have shown that oil vapourization depends on pressure, temperature, the volatility of the oil and the volume of gas cycled. An increase in any one of these conditions will increase the volume of oil vapourized.

An additional study which has recently been commenced, involves gas injection into a model oil reservoir at a relatively high saturation pressure, temperature and high oil gravity. After stabilization at the desired reservoir conditions, the model is produced under a flash liberation process. New equilibrium constant values are calculated at each liberation point to account for the changing quality of fluid remaining in the reservoir. By evaluating new mole fraction volumes of the remaining fluid in the reservoir after each liberation, curves of new equilibrium constant values versus mole fractions of remaining components in the system, are being developed. The section head of this project, Mr. A. Cook, suggests that this work will open up a whole new understanding in the field of gas cycling, and that further research by other investigators in this field may ensue.

Additional comments by Mr. Cook and other Bureau of Mines engineers relating their work and experience to possible applications in our Australian oil industry are also included in the Appendix.

(8) Routine Core Analysis. The Bartlesville station operates a small routine core analysis laboratory incorporating apparatus for measurement of porosity, permeability and fluid saturation. This equipment is mainly used for obtaining basic physical properties of core samples which may be utilized in some of the previous test programmes cited. The equipment in use has been designed and constructed by Bureau personnel. It incorporates a porosimeter, for $\frac{3}{4}$-inch diameter core plugs, which operates on a gas expansion principle; a permeameter utilizing a Fancher core holder and several sized flow rators for measuring flow capacity; and the standard Bureau of Mines Soxhlet apparatus for fluid saturation determinations. Supporting equipment in their workshop included some excellent diamond saws and drills, as well as a portable truck mounted drill for obtaining long (up to 4 feet) surface outcrop samples for special core tests.

Additional more specialized equipment in use at various times included both low and high-speed centrifuges for capillary pressure measurements, a core resistivity apparatus, and Hassler-cells for determining waterflood and relative permeability characteristics of core samples.

A one-day tour of two waterflood projects, and the Petroleum Department of the Osage Country Indian Reserve in the Bartlesville vicinity, was arranged on June 11. The party consisted of Mr. Chakraborti of the Indian Government oil agency, Mr. Harry Benyah of the Ghana Mines Department, Mr. Ken Johnston of the Bartlesville Mines Department and myself.

The first inspection was a small waterflood operation approximately 30 miles northeast of Bartlesville, in an area originally drilled in 1912. Oil production is found between 500 feet and 1200 feet in this area, a fact which enabled many small operators to establish themselves in the early years.

The eventual decline in production in the area brought about increased producing costs, and the eventual abandonment of primary production in many of the small leases. Waterflooding was subsequently introduced, bringing new life to these fields. However, petroleum production from this particular area is not generally suited to the highly automated major oil companies. Pays in this area usually consist of relatively thin sands with very high water cuts, much of which is considered border-line production. This type of recovery is usually more suited to small operators where production can be manually controlled by staff permanently stationed on the lease.

The first flood inspected was in this class - a small lease of 70 acres which is currently producing 80 barrels of oil and 2700 barrels of water per day. The produced water, together with some makeup water which is chemically treated, is filtered and reinjected at 100 to 250 p.s.i. The unit is operated by means of control valves and meters at each injection well, which are checked by the field operator, stationed on the site at all times.

Oil and water production is raised with electric downhole pumps. These have replaced beam type jack units because of their greater dependability and lower maintenance costs.

This operation typifies the small oil producer in the United States. The total oil which is produced on his leases accounts for a rather small portion of the daily production in America. He is able to stay in business thanks to the rather wisely imposed restrictions by his government on cheaper foreign oil, which if allowed unrestricted entry, would quickly make his operations uneconomic. He is a special breed who is not likely to be found anywhere else in the world.

The second operation inspected was located 50 miles west of Bartlesville in Osage County, Oklahoma. Production in this area comes from several fields, the most famous of which is the large Burbank field. Most of these fields were discovered in the early part of the 20th century and were generally very prolific producers. Osage County at one time produced 0.5% of the total world oil production.

Although recoveries from the fields in these areas have declined sharply since the flush production of earlier days, waterflooding has proved successful in maintaining an economic production level. Becasue of the large acreages involved, most of the production is held by the major oil companies (Phillips, Skelly, Sinclair and Texaco) who have unitized the leases on large producing blocks. Water for these units is generally obtained from wells along the Arkansas river; it is filtered, chemically treated and injected with produced water from the oil operations. Injection/production is controlled by Lease Automatic Custody Transfer (LACT), so that routine inspections only are required by personnel. Fluid transfer in the field is monitored by a central control; in the event of a breakdown, production is shut-in and a warning by radio is automatically transmitted to the central office.

On the return journey to Bartlesville, a very interesting and informative visit was made to the Osage Indian Agency at Pawhuska, Oklahoma. Osage county was purchased in 1873 from the Cherokees by the Osage Chief Pawhuska (White Hair); mineral rights for the county were wisely reserved by the Osages.

The discovery of flush oil production in the region in 1898 brought the first royalty payments to the tribe, with the inevitable waste and squander by the natives. Royalties continued to climb, and to protect the Indians and their rights, an agency was set up by the Government to supervise the collection of royalty payments. This amounted to 1/6th of the gross production in the county, and was distributed among the tribe on the basis of 2250 "head" rights. Payments were made directly to those natives considered able to handle their own affairs; others of the tribe had their payments withheld and invested by the Government. By 1967, the total gross income from all mineral royalties in the county paid to the tribe since 1901, reached about one half billion dollars.

Two one-day visits to adjacent oil company laboratories were arranged during the author's visit to the Bartlesville Bureau of Mines. These were a visit on June 10 to Pan American Petroleum in Tulsa, Oklahoma, and one on June 13 to Continental Petroleum in Ponca City, Oklahoma. Both trips were arranged by the Bureau of Mines, the latter one in the company of Mr. P. Lorenz, Reservoir Properties section of the Bureau of Mines.

PAN AMERICAN PETROLEUM, TULSA, OKLAHOMA.

The visit to this laboratory was commenced by a tour through the routine core analysis section. This laboratory was the largest of all the commercial facilities visited in the United States. Included was equipment for conventional and whole core analysis.

Porosity in this laboratory is evaluated by the familar Boyle's-Law (gas expansion) apparatus. The equipment in use for determination of porosity in small plugs is designed so that the expansion chamber and manometer are an integral unit. The manometer tube has been carefully calibrated to give very accurate readings.

Conventional permeability samples of $\frac{3}{4}$ inch diameter and 1 - inch length are tested in a Fancher type core holder, with pressure across the core being measured by a mercury manometer, and the outlet flow from the core being evaluated by a water manometer and an orifice.

Fluid saturation measurements for conventional analysis consisted of Soxhlet apparatus similar to the Bureau of Mines type. Flasks are loaded with approximately 40 grams of sample taken adjacent to the porosity-permeability plugs; a drying agent is used at the top atmospheric outlet of the extractors to prevent condensation of extraneous moisture (humid-air) in the condensing tubes.

Equipment was also available for permeability evaluation of semi-consolidated cores, by mounting the sample material in tooth-paste tubes, having a wire screen end face. A Hassler-cell core holder was used to retain the tubes; permeability was determined with the manifolding as described above.

Several petroleum producing areas in which Pan American has an interest produce from vuggy or fractured reservoirs; this type of core material is not suitable to conventional plug analysis and has necessitated the use of whole core porosity and permeability equipment. The apparatus is basically an enlargement of the conventional plug analysis equipment, except that a Hassler type core holder is used for measuring permeability, adopting screens for permitting flow in a horizontal direction. The porosity apparatus operates on the gas expansion principle as in conventional analysis, but is enclosed in a moisture controlled air-conditioned room to minimize transient temperature corrections.

Considerable research has been conducted by Pan American on whole core extraction methods. The present method involves the use of carbon dioxide dissolved in hot toluene at 1000 p.s.i. when enclosed in a steam heated steel pressure tube. The tubes are subsequently slowly bled down to atmospheric pressure, the CO_2 driving off most of the internal core water. Cores which are exceptionally dirty can be cycled through extraction several times. However, some care must be taken in the presence of sulphur and gypsum, so that solution of these minerals does not alter the pore space.

The special core analysis facilities seen at Pan American included equipment for the study of relative permeability, wettability and overburden pressure investigations.

The relative permeability tests are of a very complex operation and are conducted by the steady state (constant volume) method using a three-phase system (gas, oil and water). The tests are carried out at approximately five or six different stabilized flowing volumes to establish the relative permeability curves. Production was measured by an X-ray differentiator which could distinguish the phases being produced and the relative volumes of each. Pressure was determined at three points along the sample for most precision. Gas-oil relative permeability tests are also conducted, but by the unsteady state (constant pressure) method, whereby an increasing gas saturation displaces a decreasing oil saturation from a core. The gas and oil phases are separated for individual measurement at a capillary head on the outlet plug.

Compressibility (overburden) tests. The effect of rock compression caused by the weight of overburden strata involves the measuring of porosity and permeability at various confining pressure, and comparing results to some initial values obtained under routine tests.

The apparatus consists of a steel Hassler cell capable of containing 17000 p.s.i. static pressure. A sample saturated with oil is placed in the cell, and subjected to a low (approximately 200 p.s.i.) sleeve pressure. Permeability with respect to oil is determined at this and some additional increased confining (sleeve) pressures up to 10,000 p.s.i. The flow capacity at each confining pressure is plotted as a function of the permeability at 200 p.s.i. Permeability reductions as great as 75% have been noted in these tests.

The effect of overburden weight on porosity is usually not so marked as it is on permeability. Generally, reductions in porosity at high sleeve pressure are not greater than 10%, nevertheless this degree of reduction of porosity is significant in the evaluation of petroleum reserves.

The technique involved is simple; the amount of oil displaced from a fully saturated core by some high confining pressure is measured in a calibrated tube attached to the core effluent. This volume less the cell expansion approximates the reduction in pore volume due to the overburden, represented by the confining sleeve pressure in use. A normal overburden pressure value is usually assumed to be 0.5. to 0.6 p.s.i. per foot. This represents the average weight of sedimentary rocks equivalent to 1 p.s.i. per foot of depth minus the normal hydrostatic pressure of 0.43 p.s.i. per foot of depth in a reservoir.

The measurement of acoustic properties of reservoir core samples is also carried out in this section. Both low and high frequency signals are propagated through the longitudinal axis of brine saturated core samples at varying overburden pressures; travel time of these signals is determined on an oscilloscope. It has been found that travel time is independent of the signal frequency, and that certain frequencies propagate better than others through certain rock types.

The object of this work is to evaluate the relationship between rock type, overburden pressure and travel time of a signal propagated through a core. This work will have considerable application in the interpretation of sonic logs.

Wettability. The study of wettability in most petroleum research laboratories involves the use of fresh (preserved) reservoir core samples, and native oils. Pan American has taken a somewhat unconventional approach to this work. They consider that results from such tests are not always conclusive, because of the transient nature of wettability when cores are withdrawn from a bore hole and exposed to the atmosphere.

The laboratory has developed tests whereby pure crystals of a rock type are substituted for a sample of core; pure silica representing sandstone and calcite for limestone. Droplets of native oil are placed between two of these similar crystals in an environment of simulated formation water. By slowly moving one crystal with respect to the other, the droplet of oil is slowly displaced. Polaroid pictures (Figure 1) are taken throughout, to record the progression of drop distortion up to its maximum. This allows the operator to evaluate the contact angle of the oil with the crystals.

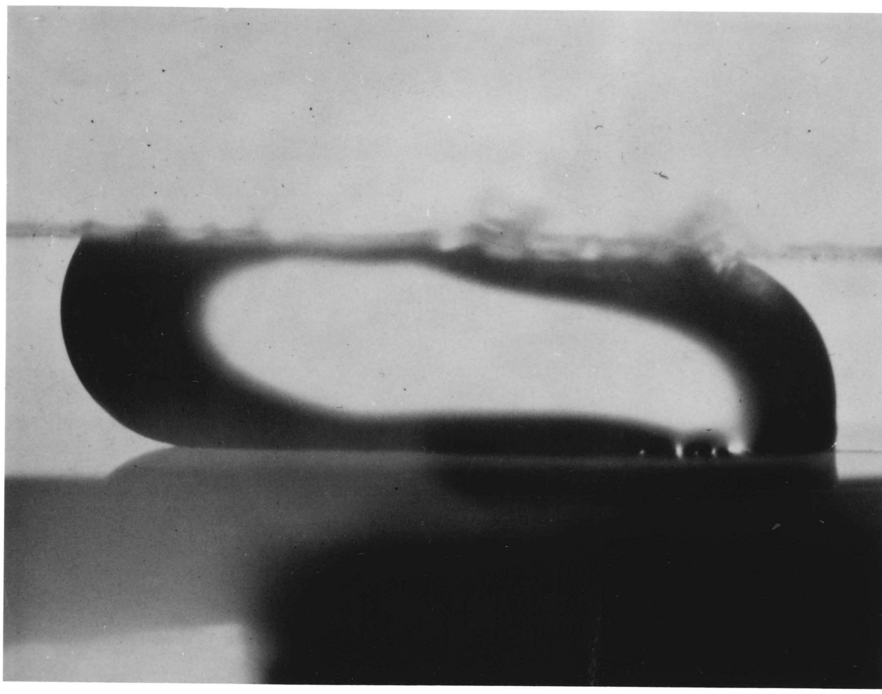

Figure 1: Enlarged photograph showing a droplet of native oil between two crystals of silica in a simulated formation water environment. The crystals are moved vertically together until the drop becomes elongated; one crystal is then displaced parallel to the other in a horizontal plane to achieve maximum distortion of the oil droplet. The contact angle of the oil with the crystal is measured directly on the photo. (Scale approximately 10X).

The second stage in the test is conducted to evaluate the effects on the oil drop of various surfactant additives in the simulated formation water. The maximum change in wetting properties is then weighed against the cost of the additives, to assist in determining the best economics for a water flood of that particular oil. Although this work is strictly qualitative in nature, Pan American feel that these results can be more usefully employed in reservoir evaluation than tests carried out with preserved core samples having transient wetting properties.

CONTINENTAL PETROLEUM, PONCA CITY, OKLAHOMA.

On June 13, a visit was made to the petroleum laboratories of this company. These are Continental's main laboratories, for carrying out research on all their domestic operations.

The initial stages of the visit were spent in the routine and special core analysis laboratory. This is a large combined facility, employing a very full complement of equipment.

In the core storage area adjacent to the laboratory, cores sealed in large durable plastic bags are received from the field. Continental does not approve of freezing cores for preservation during transfer from a well. They contend this develops fractures along planes of weakness.

Prior to any analysis, all cores received in the laboratory are photographed, so a permanent record of fractures, lithology, vugs, etc., is obtained. Then porosity and permeability plugs are cut out, using a double bladed saw, giving $\frac{3}{4}$ inch cube samples. The plugs are extracted in a centrifuge apparatus which was originally developed by Continental.

The gas permeameter for these cube plugs is a standard type in which the inlet pressure is measured by a mercury manometer, and the flow rate through the sample by a calibrated orifice. However, a rather unusual Hassler-cell, developed to seal square samples is used rather than the normal Fancher holder generally employed. The end plugs are operated by a pneumatic ram, making the operation quite rapid. The ram and Hassler-cell have the advantage of maintaining an equal controlled confining pressure on all samples.

Porosity is determined with a modified Boyles-law apparatus; the core plugs are analysed after the equipment is calibrated with steel blanks. Bulk volume measurement is carried out in a transparent cell in which mercury is displaced by a metered pump.

Fluid saturations are performed by the standard Bureau of Mines Soxhlet method, using either toluene or tri-chloroethane as a solvent.

Sidewall cores are very rarely analysed by Continental as they do not have faith in the reliability of the data. When core analysis of particular intervals in a well are required, and no core is available, they have resorted to Tri-Core, a recent development of Schlumberger and Core Laboratories. This is a continuous sidewall sample taken from the bore wall by a tool incorporating two angled diamond saw blades. Triangular samples $1\frac{1}{2}$ inches on each side, approximately $1\frac{1}{8}$ inches into the bore wall and up to 5 feet in lenght can be taken with this equipment. The section is usually an undisturbed representative part of the formation, permitting a much more accurate measurement of porosity and permeability than percussion-type sidewall samples.

Special core analysis equipment in the laboratory consisted of water sensitivity, water flooding, gas-oil and water-oil relative permeability, capillary pressure and rock compressibility apparatus. Most of the equipment and techniques are similar to those used in other laboratories. However, the following interesting points were noted:

Water sensitivity. These were performed using a bank of Hassler cells, so that a number of cores can be tested at one time with the same fluid. Tests are run by measuring flow capacity of successively weaker brines, down to fresh water. Two or three pore volumes of each solution are usually displaced through the cores before flow readings are taken.

It is interesting to note that Continental do not use the "Klinkenberg" values as a "base" permeability in these tests. They do not consider it significant of reservoir permeability, and instead, prefer to use flow capacity determined with a strong brine as the "base" for their water sensitivity tests.

Relative permeability. Both gas-oil and water-oil relative permeability determinations are conducted in this laboratory. The apparatus used is the conventional rubber sleeved Hassler-cell, with nitrogen and brine as the respective displacing phases, by an unsteady state drive.

However, they have been experimenting with new methods of obtaining relative permeability, especially to replace the present water-oil tests. It is probable that a change to the two phase steady state technique may take place, in order to circumvent some of the problems associated with certain core samples in unsteady state drive.

Capillary pressure. The time-proven (porous-plate) restored state method of determining capillary pressure is used by Continental, with humidified helium as the phase displacing the core fluid. A mercury injection capillary cell is also available, but is mainly used for the evaluation of pore size distribution, or occasionally to determine the capillary pressure of very tight samples. The evacuation of air from the samples in the mercury pump pycnometer is not carried out by Continental, the contention being that none of their cores have pore sizes which would be saturated below atmospheric pressure.

Compressibility studies. These tests involved the measurement of four different parameters - porosity, permeability, acoustics and electrical resistivity. The first three of these tests were carried out in much the same manner as at Pan American - basically measuring the change in the various properties with increased overburden pressure.

The measurement of resistivity with overburden involves a moderate conversion of the apparatus used for determination of the acoustic properties, by incorporation of electrodes in the end faces of the pressure cell. Measurements may be taken at any desired confining pressure, the resistivity increasing with increased overburden pressure. Unfortunately, these tests were not in progress during my visit because of a severe staff shortage.

Miscible displacement. Continental has been active in the evaluation of methods to increase oil recovery by miscible flooding. In a very short visit to this facility, the technique of this (laboratory) operation was explained to me.

Berea sandstone core samples, mounted with attached flow tubes in epoxy resin, are placed in metal pressure sleeves. The cores are saturated with brine, then displaced to residual water saturation with oil. A miscible flood is then performed, and the relative economics of the system evaluated. These tests, which are conducted on linear 2 foot, and large 4 foot square slabs (the latter simulating a five spot flood), can also be performed subsequent to a conventional water flood, simulating a tertiary recovery process.

The laboratory staff expressed confidence in their tests to date, suggesting that interesting applications to field tests might shortly be forthcoming. However, because of the confidential nature of the work, and the fact that certain patents on their displacement processes had not yet been granted, no indication of the actual fluids being utilised was given.

UNITED STATES BUREAU OF MINES, MORGANTOWN, WEST VIRGINIA

The Appalachian region of the United States is reputedly the oldest continuous petroleum producing area in the world. The first oil well was drilled by "Colonel" Drake in the region near the little town of Titusville, Northern Pennsylvania in 1858. This discovery, the famous Drake well, ushered in a period of flush production in the surrounding area. Unfortunately, it was also a period of great waste; little was known of reservoir forces in those days, and it was common to produce wells as fast as or faster than the oil could be transported (horse and wagon) to market; this practice resulted in early water coning and rapid depletion of natural drives. It is estimated that 80% or more of the oil was left in the reservoirs in most fields because of inefficient production methods.

The introduction of waterflooding in 1921 to the Bradford, Pennsylvania, area brought a new life to some of the old depleted fields. Many secondary recovery projects were commenced throughout the region as a result of (some) successful early trials. However, engineered planning in most of these water injection projects was often lacking, and numerous projects ended as costly failures by early water breakthrough or plugged-off (water sensitive) formations.

In order to study some of these special engineering problems, and to raise the productivity and recoverable reserves in the area, the United States Bureau of Mines opened a petroleum laboratory in Franklin, Pennsylvania. This was later moved to the present location in Morgantown, West Virginia in 1958, where joint research on conservation of coal and oil resources was located. This also gives an easy access to the coal and oil producing areas in the surrounding states of Virginia, Pennsylvania, New York, Ohio and Kentucky.

The generally low productivity of many Appalachian petroleum reservoirs has caused the Morgantown laboratory to direct much of its attention towards the study of basic reservoir properties; to answer the question of why only 5% - 25% of the oil in place has been recovered, and to discover ways to increase this recovery. They have enlisted the aid of a number of oil producers in the area for this work, in order to obtain cores for their various studies. The Bureau of Mines has also drilled wells in producing reservoirs at government expense in order to get specific information.

During the past two years, five main studies have been in various stages of investigation in their laboratory. These were:

1. Susceptibility of Eastern U.S. reservoirs to new recovery techniques.

2. Increasing oil recovery by various fluid injection techniques, including emulsions mixed by ultra-sonics.

3. An investigation of the basic physical properties of Appalachian region petroleum reservoirs rocks and fluids.

4. A study of fracture orientation in petroleum reservoirs and its application to increased oil recovery by improved knowledge of well (fracture) communication.

5. Use of heat to stimulate petroleum production.

The source of basic data for the greater part of these studies is the routine and special core analysis laboratory. The routine section of this laboratory is the largest and most active facility witnessed during the author's visit to the U.S. Bureau of Mines. Equipment regularly in use included routine porosity, permeability and fluid saturation apparatus; capillary pressure, water sensitivity, relative permeability, resistivity and water flooding test equipment.

A most advanced type of porosimeter is in use by the Morgantown laboratories. This apparatus, working on a gas expansion principle, is electronically controlled. On insertion of the $\frac{3}{4}$-inch diameter sample plug in the core chamber, an operator can automatically obtain a grain volume measurement on a calibrated scale. Calibration runs are made with measured steel blanks. Some difficulty has been experienced with the apparatus because of leaking solenoids and seals, and a slight wear in the mechanical linkages. However, when minor technical problems are solved, considerable scope exists for the equipment in rapid analysis and automatic recording of data.

Special core analysis equipment in use consisted for the most part of standard conventional apparatus as used in other laboratories. Capillary pressures are determined by the restored state or centrifuge method, while the use of Hassler-cells was common in all fluid tests such as liquid permeability, water flooding and relative permeability. A special high density transparent plastic is employed for fluid transfer cells, and can be operated at reasonably high pressure with safety.

The apparatus for evaluating core electrical resistivity employs a wheatstone bridge to measure resistance of the samples. During my visit, a new type of conducting rubber called "Echoshield" was being tested for providing uniform contact over the core face, and minimizing distortion of the current pattern near the core ends. However, reproducibility of results using "Echoshield" was not good ; it appears that the time proven platinium wire or mercury contact points are still most satisfactory.

Two additional pieces of apparatus of note, conceived and developed by the laboratory, included a directional permeability device, and an apparatus for measuring directional resistivity. The former employs a radial flow measurement whereby a full $3\frac{1}{2}$-inch diameter core is placed in a core cell consisting of 24 steel vanes set 15 degrees apart around the core perimeter. Fluid flow radiates from a small hole drilled axially into the core centre; production is measured in calibrated tubes between the vanes on the circumference of the core.

The resistivity device utilises the core sample from the directional permeability test. A current electrode is lowered into the central hole, and slowly rotated, while the potential difference between the current electrode at the circumference of the core is recorded.

Although some technical difficulties still exist with these two pieces of apparatus, it is expected that patents will shortly be applied for in respect of both items. Considerable use will be found for them in the current studies of directional flow properties and fracture orientation in Appalachian area reservoirs.

In another part of the core laboratory, the effects of additives on secondary and tertiary oil recovery by water flooding are determined. These tests are conducted in an all plastic cell, containing a sand pack core. The core is saturated with brine, displaced to residual water saturation with oil, then again brine flooded. Subsequent to obtaining residual oil saturation a second flood is conducted using brine containing a surface active agent. Concentration of the detergent solutions contained from 0.1 to 2% surface-active agent and were injected as a slug (approximately 0.1 to 0.25 pore volume). During the author's visit, a commercially available detergent, classified A-II (as used in the Torrey-Canyon disaster) was being tested.

Because of the low productivity of most producing reservoirs in the Appalachian region, and the poor sweep performance of some regional water flood projects, the most active programme at the Morgantown laboratory in progress of late is the study of joints and fracture orientation. This involved both surface and subsurface investigations. The surface studies covered aerial photographs, relief maps, stream drainage analysis, and field study of joints in road cuts, quarries and outcrops. The subsurface work involved oriented core investigations, impression packer surveys and down-hole photographs, plus pulse pressure testing of wells. This study has attempted to relate the surface to the subsurface regional joint and fracture patterns, both induced and natural to gain a better understanding of the effects of productivity in a reservoir.

An interesting relation has been established between this study and early day oil production in the area. With reservoir engineering technology in the 1860's almost non-existent, oil explorers of that era believed (most logically) that petroleum would be found below stream beds where the oil flowed in its own stream channels underground. This theory was substantiated by the number of seeps and early discoveries drilled near the creeks and rivers (Oil Creek, Allegheny river, etc.) and the relatively "barren" drilling which occurred in the surrounding higher country.

The current fracture study has revealed a more logical explanation to these theories. Recent investigations have shown that the stream beds in the Appalachians often lie along the surface expression of fractures which may extend to considerable depth, the fracture offering the least plane of resistance to the streams in their meanders. Petroleum was also more easily able to migrate at depth along these fracture planes to reservoir traps, thus developing (occasionally) surface seeps and permitting a good discovery ratio in reservoirs bisected by numerous parallel subsurface fractures (along the stream paths).

The subsurface studies have involved the measurement by impression packer (using uncured rubber) of induced hydraulic fractures around well bores, in addition to directional core tests and down-hole photographs.

These tests have generally confirmed that the measurements made at depth have corresponded in direction with the surface findings. It is hoped that sufficient data can be gathered on a number of areas in the Appalachian fields to help predict better waterflood sweep performance and also assist in siting and drilling of new wells.

During the Morgantown visit, two field trips to Pennsylvania were taken by the author in company with Bureau of Mines staff. These were a short trip to Indiana, Pennsylvania, to collect a core from a gas field well, and an inspection trip to Kane and Titusville, Pennsylvania, to discuss possible thermal recovery projects by the Bureau with operators in this area.

The first location visited at Indiana (50 miles east of Pittsburgh) was a well being drilled by a local gas supply company. Production in the area is mainly from shallow stratigraphic traps in Devonian and Mississipian sandstones. Wells are generally of low productivity; however a good price can be obtained for natural gas in this area, and combined with low cost drilling, a well can bring a good capital return on an investment.

Air drilling is often used in rotary drilling operations in Pennsylvania and this method was used in the well visited. A detergent foam was injected into the air stream for coring operations, to give added lubrication and temperature control to the diamond core bit.

During the visit, two cores were taken. The first recovered two feet of shale with slight sand stringers; the second recovered nine feet of shale. Electric logs of the upper intervals indicated good correlation with an adjacent gas well containing a good sandstone producing section; a pinch-out of the producing pay had evidently occurred. A considerable number of the wells from which the Morgantown station hopes to obtain cores for additional basic information are of this category. Many are drilled as edge wells on old producing fields; these have now become permeable, economically productive zones through the advent of modern high pressure formation fracturing techniques. At the same time, an excellent opportunity is available to gain some basic reservoir information on these old fields, where none was ever obtained before. However, pinch outs of the productive pay on edge wells, as occurred in the well described above, are common and it is often necessary to obtain cores from other sources.

The second field trip (June 25-27) to the Kane - Tittusville area of northern Pennsylvania, covered two field projects and other areas in which the Morgantown laboratory has had an interest. These included a fire flood project in the Reno oil pool, Venango County, Pennsylvania, and a pilot waterflood project in McKean County, Northern Pennsylvania.

The fireflood in Venango County was conducted in a low permeability sandstone at a depth of 550 feet in 1963. The pilot area consisted of 8 acres with a single injector, and 6 producing wells. A 65:1 mixture of air and natural gas was injected for 18 hours before ignition of the formation was attempted. However, after several trials, it was found that ignition in the reservoir was not self-sustaining because of insufficient fuel in the formation, too high an ignition temperature and an incorrect ratio of air-gas injection mixture.

Although the thermal experiment was unsuccessful, the effects on some of the edge wells on the field have been noteworthy; production from these (hydro-fractured) wells prior to the thermal test was very low, but productivity rose steadily subsequent to the tests, some wells producing up to 60 barrels per day. On this basis other wells were drilled on the perimeter and most made good producers after fracturing. It appears the injection programme in the pilot flood area had some positive effects on migration of oil to the edge wells.

The field trip was continued from the Reno field, north through the old producing areas of Oil City, Pithole and Tittusville. Most of the production in these areas has long since dwindled to a trickle of the former flush production before the 20th century. The state of most wells and production equipment in these fields today is of remarkable antiquity, with the production measured in tenths of barrels per day. Some wells are only pumped for a few hours each week, depending on the processes of imbibition and stabilization to allow a few barrels of oil to be produced on each cycle.

The final phase of the field trip was spent in the Kane oilfield. This waterflood was initiated on a 36 acre pilot, on encouragement by the Bureau in 1963, after predictions from field and laboratory studies by Morgantown indicated a favourable recovery of 27% pore volume by water flooding.

The Kane oilfield in particular was selected for investigation, as part of a study to increase oil reserves from known pressure-depleted reservoirs of the Appalachian area. The operator suggested the pilot test area, and co-operated fully with the Bureau on the project.

A comparison of the theoretical and actual waterflood results in this field is a classic example of the problems confronting many secondary recovery projects in the Appalachian region. Shortly after inauguration of this flood, water cut at the producing wells in the pilot area increased considerably; a fluorescine dye tracer test to check this, indicated direct or near miss fractures communicating with the producing/injection wells. In addition, it was ascertained shortly afterwards that the initial gas saturation estimated for the prediction recovery had been erroneously high (i.e. the oil saturation had been computed as too low a value). The net result of these two conflicting conditions was a recovery approximating that as predicted, and the operator put considerably more of his production under flood.

Secondary and tertiary recovery projects such as this one are further hampered in these initial predictions by a dearth of field history concerning the recovered reserves, original bottom hole pressures, gas caps, gas-oil ratios, and a host of additional information necessary for a well developed waterflood programme. With Pennsylvania grade crude bringing the highest prices for any oil in the U.S.A., it is apparent that a continued study by the Bureau of Mines is quite warranted, in order to resolve the numerous unknowns in these reservoirs, to increase recoverable reserves and help to bring a greater return to the numerous oil producers in the area as well as to the government.

GULF OIL RESEARCH LABORATORY, PITTSBURGH, PENNSYLVANIA.

On July 10, a visit was made to the research laboratory of Gulf Oil Company in Pittsburgh, Pennsylvania. This is a very large establishment, located in the northeast of Pittsburgh. Gulf has maintained the Head Office in downtown Pittsburgh for some years, and this laboratory is the main research facility for its world-wide operations.

The initial phase of this visit was spent with the manager of exploration research, Mr. Ross. He reviewed the current research of his group, and especially emphasized the work of their world-roving research vessel "The Gulfrex". This boat is equipped with a number of seismic and geochemical devices including "sparker" equipment for shallow seismic investigations, and continuous chromatography for determining possible hydrocarbon concentrations in the sea. This vessel will be exploring a considerable portion of the free world's continental shelf areas in the next 1½ - 2 years.

Some interesting work in the realm of depth of burial and its relationship to porosity were being conducted in the geological section under Mr. G. Pardo. His work has involved the evaluation of porosity changes with increasing confining pressure (net overburden) down to an equivilent pressure simulating 20,000 feet in depth, this being done in an overburden pressure cell.

A theoretical study of the same relationship has also been conducted using a formula incorporating temperature gradient for a particular area.

Remarkably good correlation has been observed between the theoretical values and measured porosities from ultra deep wells. However, data from samples tested solely under increased confining pressure in the laboratory have not compared favourably with the above results, indicating other effects have to be considered. Although considerable work remains to be done, present evidence suggests that porosity reduction with depth is due to a combination of overburden pressure and temperature. However, temperature probably has the most positive effect on consolidation of core material; siliceous clays and calcareous cementing material present in pore channels and interstitial water, act as very strong bonding agents between sedimentary grains when acted upon by temperature.

Gulf has also been investigating acoustic properties of core samples with varying overburden pressures. These tests more or less parallel those witnessed at other laboratories. However, it was noted that studies were also being carried out with unconsolidated sand-pack cores mounted in thin flexible sheathing. These were subjected to various moderate overburden pressures and low frequency signal propagation. The travel time through these sand-pack cores will be of assistance in interpretation of sonic-log investigations of shallow unconsolidated core material.

Other advanced testing in this field involved some very costly equipment for determining the refraction and reflection characteristics of slabbed core samples. These were rotated in the presence of a very high frequency signal (mega-cycle range) until the sound, increasingly refracted through the cores, was eventually reflected when the angle of incidence became large.

The original equipment developed for these studies has now been donated to a prominent American University. Additional less complex apparatus has been put into service for Gulf in this field to continue investigations in reflection and refraction geophysical research.

Polymer flooding. The use of polymers in flooding water to improve the oil/water mobility ratio and oil recovery has been extensively studied by Gulf using a pieshaped laboratory model representing $\frac{1}{8}$th of a five spot field flooding pattern. In this field, Gulf has conducted numerous polymer-floods in sand-pack cores simulating both homogeneous and stratified reservoirs.

Gulf's reserach to date has caused it to be less optimistic than some of its competitors. It has been found by Gulf that the effectiveness of polymers in a water flood becomes reduced with distance from the injection point. Investigations have pointed to the fact that in a number of cases, the polymers in use have been absorbed on the sand grains, thus reducing polymer strength (and effectiveness) with distance from the injection well. Several tests in which polymer floods and fresh water floods have been conducted in identical sand pack matrix, have shown the normal waterflood to be nearly as efficient in displacing oil as the thickened-water-polymer flood. When the economics of the situation are studied, the polymer flood does not appear as attractive as generally considered.

Gulf considers that these discrepancies with the findings of theoretical studies in other laboratories may be a result of the choice of equipment. Hassler-cells may not show up this absorption effect because of a more uniform displacement through the samples. Research in this field is continuing; indications are that a polymer is much more effective if used with a surface active agent in the flooding water.

Thermal recovery. The latter portion of the visit to Gulf was spent in its thermal recovery section. This phase of the work has involved the use of linear cylindrical sand-packed models and a large (4' x 4' x 6") stainless steel sand-pack model. The tests with the sand-pack tubes are quite conventional. However, the large steel reservoir is unusual in that it has been packed inside an even larger cylindrical pressure cell. The model is filled with an oil saturated sand-pack, and numerous temperature sensors are placed on the exterior. The space between the model and the pressure cell is filled with crushed glass slag, to simulate overburden heat losses etc. Tests are run using approximately 75 p.s.i. overburden pressure surrounding the model. This has the effect of flexing the thin steel shell and consolidating the model, thus more closely approximating reservoir conditions.

Mathematical model studies. A very brief discussion was held with Mr. H. Price of Gulf's mathematical model studies section. The basic technique of this group is to divide a particular reservoir into a grid pattern. Then, considering all the physical parameters and characteristics available in the field, they proceed to evaluate all the possible ways in which the reservoir could be produced.

The object, of course, is to obtain the most economic method of production for any given reservoir; this approach has been applied to many of Gulf's domestic and foreign reserves. Computers have been an invaluable service to this work, and are used extensively for their various predictions and calculations.

CONCLUDING OBSERVATIONS

The planning of operations and studies in each of the laboratories visited during this trip involves a considerable amount of organizing and foresight on the part of directors, coordinators and section leaders in each establishment. The programmes, as adopted, develop from a number of different sources.

Operations in the commercial laboratories are in no small part governed by the requirements of the respective company field operations. However, research which is conducted by these groups, usually develops from suggestions by top management or directors, when it is recognised that investigations in a particular direction are warranted. Competition from "outside" sources often governs the purpose and direction of much of the research carried on; this may lead to a particular company achievement which will give them an edge on their competitors (such as Marathon's Maraflood process) and have far reaching effects on their future earnings and development.

The Bureau of Mines on the other hand, is in a somewhat different category, inasmuch as it is concerned with the national petroleum industry as a whole.

Encouragement of the development of new recovery techniques, pressure maintenance and conservation are only a few of the many areas of the Bureau's concern. In general, this body acts as a subtle industry "guide" to encourage the maximum efficient recovery of the nation's petroleum resources.

The following is an abbreviated list of sources for the Bureau's* programmes:

(1) American Petroleum Institute.

(2) Independent Petroleum Association of America.

(3) Industry - Bureau of Mines Research Study Committees.

(4) Other government agencies (such as the Armed Forces).

(5) Research requests by private companies.

(6) Programmes initiated by supervisors within the Bureau.

(7) Literature surveys.

In the operation of large companies and government organizations such as with those visited on this trip, the question arises as to what constitutes a successfully run group. Is the main criterion of this, good planning, skilled manpower, good management - employee relations, work stimulus, or company loyalty? A well run organization probably encompasses all these factors, but salary scales, and encouragement of a creative thinking and work are the two most important. This was especially noted at the Bureau of Mines. Salaries paid by this organization are comparable with the petroleum industry level; indeed, employees with three to five years service were generally reimbursed at a better rate than those in industry.

The primary effect of this policy has been the attraction of people with the required experience to their particular discipline within the Bureau of Mines. This facility in obtaining skilled engineers, geologists and technicians, has made it relatively easy successfully to carry out research and development programmes of a high order as described in this report.

In Appendix 1 of this report, a table of salary levels for U.S. Federal Government employees is shown. This schedule is graded from G.S. -1 to G.S. - 18; these salary levels roughly correspond to Bureau of Mineral Resources classification from Technical Assistants to Directorial positions. In addition, each G.S. level in the U.S. Federal service has a 10-step salary differential giving employees (on their merit) a considerable pay range within their G.S. level.

A direct comparison of positions and salaries between the U.S. Bureau of Mines and the Australian Bureau of Mineral Resources is somewhat difficult due to the variations and scope of comparable positions in each system. However, an approximation of comparable positions and salaries (Australian dollars) is noted as follows:

EQUIVALENT POSITION/SALARY LEVELS.

U.S. Federal Service Bureau of Mines.			Australian Commonwealth Service, Bureau of Mineral Resources.		
Designation	Scale	Salary Range (Australian Dollars)	Designation	Scale	Salary Range (Australian Dollars)
Petroleum Engineer or Geologist (No experience)	G.S.-5	5117-6657	Pet. Technoligist or Geologist (No experience)	Class-I	3037-4890
Petroleum Engineer or Geologist (Several years Experience)	G.S.-7 G.S.-9	6233-8105 7555-9821	Pet. Technologist or Geologist (Several years Experience)	Class II	5104-5761
Project Leader	G.S.-11	9109-11842	Pet. Technologist or Geologist	Class III	5975-6611
Project Coordinator	G.S.-13	12865-16722	Pet. Technologist or Geologist	Class IV Class V	6864-7370 7640-8194
Supervisor			Assistant Director		
Director			Director		

This report describes a variety of tests and research studies which were being conducted at the various facilities visited. A small portion of these studies, such as the nuclear investigations, were highly complex requiring the employment of rather costly equipment and personnel with a long experience in this particular field. Other phases of the work witnessed were related to a petroleum industry classified as "well-matured"; this work would cover tertiary recovery experiments, and some forms of thermal recovery investigations. At the present time, these studies would not have any great significance in our Australian operations, as would some other investigations.

The fields of secondary recovery and pressure maintenance probably provide some of the most promising avenues for adoption by our laboratories of some of the expertise of our American counterpart. Investigations by their laboratories and numerous other similar bodies have generally shown that early introduction of some form of pressure maintenance usually has a beneficial effect on the ultimate recovery of oil from a reservoir. We, therefore, have an excellent opportunity to capitalize on these investigations, by applying some of this work in our laboratory to cores from reservoirs which have only recently experienced production drilling.

Based on the work witnessed in the United States, the following is a brief list of some possible investigations which could be adopted to our programmes:

(1) The investigation of waterflooding recovery characteristics before and subsequent to pressure depletion by solution gas drive.

(2) The effects of overburden pressures on porosity and permeability.

(3) The study of wettability, interfacial tensions, and additives, and their effects on waterflooding.

(4) Polymer and miscible phase flooding tests.

Additional investigations which could be conducted at a later date, contingent upon obtaining more professional staff, equipment and space are as follows:

(5) Investigations of multi-phase fluid flow.

(6) Studies of capillary pressure by the centrifuge method. This also partly applies to point (1) above, in which a centrifuge and pendant drop apparatus are mandatory.

It would be unwise to move blindly ahead in this work programme without again drawing on the past experience of the Bureau of Mines in America. As noted, they have organized a number of sources from which useful suggestions and recommendation for their study and research programmes originate. The same plan could also be applied to operations in our Petroleum Technology Laboratory as suggested below:

(1) A Bureau of Mineral Resources - Petroleum Industry Committee, set up to study and approve proposed studies and research. The frequency of these discussions could be decided at the first meeting.

(2) The Australian Petroleum Exploration Association with its wide industry contacts could probably recommend research investigations which would be of benefit to the whole petroleum industry. Some of this work could be presented as papers to its annual meetings.

(3) More frequent personal contact with the States Mines Departments, to sound out their requirements. This could have the added benefit of facilitating the provision of core samples for our work.

Other sources of work programmes and ideas could be developed for our laboratory operations. However, with the present limited professional staff, finances, space and equipment, it is felt the above suggestions would be adequate for our present abilities.

(B.A. McKAY)
<u>Petroleum Technologist, Class III.</u>

APPENDIX I.

U.S. FEDERAL SERVICE SALARY LEVELS

G.S. Level	G.S. Level Salary Range (U.S. Dollars)									
	1	2	3	4	5	6	7	8	9	10
1	3889	4019	4149	4279	4408	4538	4668	4798	4928	5057
2	4231	4372	4513	4655	4796	4937	5078	5219	5360	5501
3	4600	4753	4907	5060	5214	5367	5521	5674	5828	5981
4	5145	5316	5487	5658	5829	6000	6171	6342	6513	6684
5	5732	5924	6115	6207	6498	6690	6881	7073	7265	7456
6	6321	6532	6743	6955	7166	7377	7588	7799	8010	8221
7	6981	7214	7447	7680	7913	8146	8379	8612	8845	9078
8	7699	7956	8213	8470	8727	8984	9241	9498	9755	10012
9	8462	8744	9026	9308	9590	9872	10154	10436	10718	11000
10	9297	9607	9917	10227	10537	10847	11157	11467	11777	12687
11	10203	10543	10883	11223	11563	11903	12243	12583	12923	13263
12	12174	12580	12986	13392	13798	14204	14610	15016	15422	15828
13	14409	14889	15369	15849	16329	16809	17289	17769	18249	18729
14	16946	17511	18076	18641	19206	19771	20336	20901	21466	22031
15	19780	20439	21098	21757	22416	23075	23734	24393	25052	25711
16	22835	23596	24357	25118	25879	26640	27401	28162	28923	
17	26264	27139	28014	28889	29764					
18	30239									

APPENDIX 2

Several comments of interest to our Petroleum Technology Laboratory and the Australian petroleum industry in general were made by Bureau of Mines engineers during my visit. These do not pertain to any particular phase of work, but are listed here as of general interest. However, their significance should not be underestimated, for they were made by men of considerable experience in their particular fields.

Mr. Cecil Cupps - Project Co-ordinator, U.S. Bureau of Mines, Laramie, Wyoming.

On new field discoveries, Mr. Cupps suggested the following: The industry governing body in Australia should encourage the particular oil operating company (ies) to conduct the maximum amount of coring, petrophysical core testing and reservoir fluid studies on productive intervals in each new field. This would have the immediate purpose of permitting comparisons with other producing fields so that production methods and histories might be related for maximum efficient recovery. This information would have the secondary advantage of assisting in the evaluation of pressure maintenance and tertiary recovery projects at some later stage in the producing life of the field.

Mr. Alton Cook - Research Engineer, U.S. Bureau of Mines, Bartlesville, Oklahoma.

Mr. Cook has worked for the Bureau of Mines in the realm of reservoir fluid studies and gas injection/gas cycling projects for a number of years. He had several interesting comments to make within these particular disciplines.
In early development of new oil reserves, he stressed the importance of obtaining a reliable, representative value for the reservoir gas-oil ratio. This would be of importance in conducting future reservoir fluid studies, also in obtaining recombined samples for subsequent P.V.T. tests.
When exploration drilling has been conducted near centres of large population or extensive industrial areas; even though such wells may prove to be non-productive of hydro carbons, particular attention should be paid to the following points for future gas storage projects: dense thick cap rocks of impermeable shales, anhydrite, salt, etc., overlying permeable aquifers. Such formations may prove to be extremely useful at some later date (especially where large structural traps are involved) for injection and storage of pipeline gas from other producing areas, permitting high rates of (local) withdrawal at times of peak demand.

Mr. Clyde Pierce - Project Co-ordinator, U.S. Bureau of Mines, Morgantown, West Virginia.

Mr. Pierce has been involved for some time in petrophysical investigations in the Bureau's Morgantown Laboratory. As such, he had several suggestions which are of noteworthy application to our Petroleum Technology Laboratory operations.

Get together a committee of oil industry and key laboratory personnel to formulate project plans for the laboratory.
Develop original research projects where possible, and avoid continuous work which is of too much routine (such as basic core analysis etc.).
When selecting laboratory staff, choose people from several disciplines such as engineers, physicists, chemists and mathematicians. In this fashion, a broad scope of ideas will be available to the laboratory.
Avoid research projects which may involve an extensive amount of equipment, and then be terminated in a short time.
Always bear in mind that the governments' primary concern is of conservation of petroleum resources. Therefore, concentrate on laboratory research projects for improving the ultimate recovery in new producing areas.