TEXAS WATER DEVELOPMENT BOARD

REPORT 44

FUTURE WATER REQUIREMENTS

FOR THE

PRODUCTION OF OIL IN TEXAS

By

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FOREWORD

During the preparation of the preliminary Texas Water Plan, the Water Development Board had a number of studies prepared by The University of Texas, Texas A & M University, and Texas Technological College. Other investigations were prepared by the staff or under contracts with various consultants. A number of these reports have been published heretofore by the Board.

The projections of water requirements for secondary recovery operations for the production of oil in Texas were prepared in two forms. Dr. Paul Torrey prepared the following report under contract to the Water Development Board. Also, at the request of the Board, The Texas Mid-Continent Oil and Gas Association provided an estimation of water requirements for the same purpose. Projections by the Mid-Continent Oil and Gas Association were based upon needs in known fields, while Dr. Torrey's estimates are slightly higher and reflect anticipated additional discoveries. For this reason the slightly higher figures prepared by Dr. Torrey have been used for planning purposes.

Publication of this report is a continuation of the Board's policy of providing the widest possible distribution of information obtained in the preparation of the preliminary Plan.

TEXAS WATER DEVELOPMENT BOARD

Joe G. Moore, Jr.

Joe G. Moore, Jr.
Executive Director

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SUMMARY OF REPORT

The production of oil is an important industry of Texas, and the use of water for this purpose contributes a gross income of from $0.31 to $0.37 for each barrel of water so used. Thus, the use of water for oil production may be more profitable to the State than other industrial uses.

An estimation of the amount of water that will be required in the future for the production of oil must be based on an estimation of the amount of oil presently available and the amount of oil that will be discovered in future years, that is susceptible to recovery by the injection of water or steam into underground reserves. Therefore, a study of oil reserves is a fundamental part of a study of water requirements.

Some water is produced along with oil, but usually the amount is insufficient for successful water injection operations. Water from other sources, therefore, is essential to supplement the available supply of produced water.

The largest reserves of oil in Texas susceptible to recovery by water injection are located in arid portions of the State. Fortunately, water of inferior quality and not suitable for municipal and most industrial uses can be utilized successfully for this purpose. However, water of high quality and relatively free from dissolved salts is required for the generation of steam in thermal recovery operations.

According to the request of the Water Development Board, projections of future water requirements for the production of oil have been carried to the year 2020. The hazards associated with projections for such an extended period of time are emphasized.

The manner in which the recovery of oil can be increased by the injection of fluids into underground reservoirs is disscussed. The growing importance of fluid injection operations is stressed, and it is shown that production from them in Texas has increased from 20 percent in 1953 to around 29.5 percent in 1965 of the total volume of oil produced. It is pointed out that part of this growth is due to the fact that many secondary projects are not prorated because their production is in the marginal well classification. Thermal methods have promising possibilities for the recovery of heavy, high-viscosity crude oil in future years.

After consultation with several recognized authorities, it was decided that the only way an estimation of Texas' future requirements for water in the production of oil could be made within the time available was by mathematical projections of existing data. The deficiencies of this method are recognized but no satisfactory alternate procedure could be developed.

Texas oil reserves from known reservoirs recoverable by water injection as of January 1, 1965 are estimated to be slightly over 4 billion barrels.

Oil reserves in Texas susceptible to recovery by water injection from future discoveries are estimated to be almost 12 billion barrels. Thus, the total reserves from water injection through the year 2020 are slightly over 16 billion barrels. A satisfactory check of this figure has been obtained by a modification of a graph developed several years ago to show the future production of oil by secondary recovery methods in the United States. The trend of this graph has been adapted to Texas production and the results of such adaptation are considered to be reliable, subject to the limitations discussed in the report.

From statistics taken from reports of Texas Petroleum Research Committee, it is shown on the average that 8.2 barrels of water is required to produce 1 barrel of oil in Texas. This figure and figures for the respective Railroad Commission Districts have been verified in satisfactory manner by a review of the results of several water injection projects in various parts of the State on which fairly complete history is available.

Information developed by the Staff of the Water Development Board has been used to determine the amount of supplemental or make-up water that has been required for injection purposes in Texas for 4 recent years. This figure then has been used for the respective Railroad Commission Districts and for the State as a whole in an estimation of future water requirements.

Future water requirements for the production of oil in Texas are shown in extensive tables. From the calculations on which these tables are based it is estimated that 117.5 billion barrels of water from supplemental sources will be required in Texas through the year 2020 for the production of oil. It is also estimated that around 10.5 billion barrels of water will be required in Texas for the generation of steam in thermal recovery projects. Thermal recovery methods have been applied so recently that there is no background of experience which will enable a projection of water requirements for steam generation by successive time periods. It is mentioned that the estimated oil reserves recoverable by the application of thermal methods in Texas may be much greater than those which have been developed for the report. This is due to the fact that it has been necessary to use information based on California operations to define the gravity of crude oil that may be recovered successfully. It is also noted that underground combustion, one of the thermal methods, may be substituted for water injection in areas possessing small water resources.

Practically all water purification processes employed to improve the quality of water for municipal use produce waste water possessing a high saline content. The disposal of this waste water can be a serious problem to avoid the contamination of surface water supplies and to prevent damage to vegetation. Fortunately, it appears entirely practical to use waste water from treating plants for injection into oil reservoirs. Towns and cities recommended by Southwest Research Institute for studies of desalinization of existing water supplies, that are located in proximity to oil fields in which water injection projects are in operation or where it is believed that water injection can be employed successfully, are listed and the oil fields are identified. The town of Freer, in Duval County, is located most advantageously with relation to oil fields where large water injection projects are in operation.

Ways in which the present study of future water requirements for the production of oil in Texas might be improved are considered. The revision of the report on "Oil Resources of Texas, 1954" is considered to be essential for the development of more accurate information, for it appears unlikely that reliable figures on oil reserves can be obtained from any other sources. It is recognized that this is a job of considerable magnitude, but each year revision is delayed will make the job more laborious.

The assistance that has been received from several sources in the preparation of the report is acknowledged with appreciation.

INTRODUCTION

This report is part of a comprehensive study being conducted as a part of the planning program of the Texas Water Development Board to estimate the water that will be required in Texas by municipalities, by agriculture, and by industry in future years and to determine how the water resources of the State can best be utilized to provide for the needs of a rapidly expanding economy.

The utilization of water to increase the production of oil is one of the many industrial uses of water in Texas. Such utilization of water is one which makes a substantial contribution to industrial income and, in turn, to the support of local, county, and state governments with their associated tax-supported schools, eleemosynary institutions, and transportation facilities. As this report shows, on the average in Texas, around 8 barrels of water is required to produce 1 barrel of oil which may have a value of from $2.50 to $3.00 depending on its quality. Thus, the use of 1 barrel of water can provide gross income of anywhere from 31 to 37 cents. Such being the case, the use of water in the production of oil, in all probability, is more profitable to the State and to its people than many other uses regardless of the importance and necessity of such other uses.

The unit of volume used in this report is the oil barrel of 42 U.S. gallons. By the use of this unit of volume it has not been necessary to convert figures and units of measure which are in common use by the oil industry.

No attempt has been made to determine the availability of water for the production of oil. The formations which constitute the oil reservoirs of the State furnish only a small part of the water required for secondary recovery and/or pressure maintenance operations. Thus, it is necessary in most fields to supplement the water produced along with oil with water from other sources. It is this requirement for supplemental water which is important to the Water Development Board and to the State, and it is essential that supplemental supplies of water are available in order to permit the production of oil by water injection without interruption and at the future rate projected in this report.

It has been necessary to assume for the purpose of this report that water will be available in the quantity required for the production of oil at the projected rates. However, it is pertinent to comment, as the report clearly shows, that the greatest reserves of oil susceptible to recovery by water injection are located in the most arid portions of the State which possess limited water resources. Fortunately, for conventional water injection operations, water of inferior quality, which would not be suitable for domestic, agricultural, and many other industrial uses, can be used successfully.

This report deals principally with the use of water for conventional injection into oil reservoirs. This recovery process will be considered in some detail in a following section. Likewise, some consideration is given to the use of water for the generation of steam in thermal oil recovery operations, where water of superior quality is required.

Most of the numerical information developed for this report is listed by Railroad Commission Districts, and it has been compiled in large part from data on individual fields. It is regretted that it has not proved to be feasible to list data by river drainage basins in the manner in which the Water Development Board compiles and segregates the results of its studies.

At the request of the Board, estimations of oil production and water requirements have been projected to the year 2020. Figures are presented in most cases for 10-year periods, but the first period in the report extends from 1965 through 1970, a period of 6 years. Ten-year periods are employed commonly by the industry for such projections, for shorter periods tend to exaggerate temporary conditions affecting the production of oil.

The writer recognizes and wishes to emphasize to the Board the very real hazards associated with projections relating to future oil production and water consumption for an extended interval of 56 years, such as have been made in this report. This period of time has been employed in order to conform the findings reported herein to the scope of the Board's basic studies, but it has been used with the greatest reluctance for there are many unpredictable factors, both technical and economic, which could influence drastically the future course of oil production in the State and in the Nation. Unfortunately, it is not possible to foresee and thereby predict the effects these factors may have over extended periods of time.

It will be obvious that the amount of water required for the production of oil will depend on the amount of oil available which can be produced profitably by water injection into the reservoirs. Unquestionably, there are large reserves of oil in the United States that can be recovered by known methods but which cannot be produced profitably under existing economic conditions. Therefore, a continuation of present economic conditions must be assumed in order to project future oil production by water injection, for, if economic conditions should change, the trend of future production will change in unknown extent. The validity of this assumption is supported in part by the strong probability that there will be no substantial increase in the price paid for domestic crude oil as long as large quantities of foreign crude oil are available for import into the United States. As a matter of fact, crude oil prices have declined rather than advanced during the last decade, and the oil industry has been able to maintain profitable operations by reason of enforced economies and by improvements in oil recovery efficiency rather than by increase in the price paid for its raw material and for refined products. However, it is possible for the purpose of this report to assume some future improvement in oil recovery efficiency based on a trend that has been established after World War II.

From the preceding discussion it will be understood that a study of oil reserves susceptible to recovery by water injection is fundamental to a realistic estimation of the amount of water that will be required to produce them. In considering oil reserves, it should be understood that the quantity available in place in the reservoir is definite and fixed, and, unlike the contents of an aquifer, which can be recharged by rainfall, the depleted contents of oil reservoirs are not replenished within historical periods of time.

THE RECOVERY OF OIL BY FLUID INJECTION

A consideration of the mechanics of oil recovery from underground reservoirs is not essential to the objectives of this report. However, it is pertinent to point out that most of the fields of early discovery in the United States, and including Texas, were produced wastefully with a rapid dissipation of the original reservoir energy, and, as a result, much of the original oil content of their reservoirs remained unproduced by natural recovery processes. It was discovered many years ago that a partial or complete restoration of pressure, by the injection of gas or water into the oil reservoirs, could improve oil recovery substantially where the residual oil content was high. The injection of either fluid will serve to create a differential in pressure in the reservoir, which will cause the movement of oil into producing wells, but, since water is a better displacing agent than gas, the use of water will generally result in greater improvement in oil recovery.

Once the benefits of the secondary recovery methods were established, it became obvious that if the pressure in oil reservoirs could be maintained, rather than become depleted by uncontrolled production, even greater benefits in the way of more efficient and more profitable recovery would result. Thus, it has become common practice to initiate pressure maintenance operations early in the life of a field, by the injection of gas or water or both, so that the wells will continue to have high productive capacity up to the time of ultimate depletion. The time required to obtain the maximum economic recovery of oil is reduced by pressure maintenance operations and the volume of fluid required for injection is usually considerably less than is the case in secondary recovery operations. Similar to secondary recovery, water is preferred over gas for the maintenance of pressure, and in Texas about 85 percent of all of the secondary recovery and pressure maintenance projects use water as the injection fluid.

It is recognized that it is sometimes difficult to distinguish between secondary recovery and pressure maintenance. Actually, a precise definition is not essential to the purpose of this report, other than to point out that pressure maintenance projects in fields of recent discovery will usually require relatively less water than is required for secondary operations in the older fields. Secondary recovery connotes a second crop of oil and it is a distinct operation from primary production, whereas pressure maintenance combines fluid injection with primary production and permits the economic depletion of an oil reservoir in one operation.

The greater efficiency in the use of water in pressure maintenance operations, in comparison with secondary recovery, should be emphasized. Because the highest liquid saturation exists in the oil reservoir at the time of its discovery, water that is injected during the early life of a field will be used largely for the displacement of oil rather than to fill up the voids which have been vacated by produced oil and gas. Therefore, from the standpoint of economical use of water, pressure maintenance operations should be encouraged in all fields where the primary production mechanism will not provide an effective recovery of the oil content of the reservoirs.

The production of oil by fluid injection is of growing importance in the United States and in Texas. In 1953, 20 percent of the oil produced in Texas came from fluid injection projects. In 1960, this ratio had increased to 25 percent, and in 1965 it is believed that around 29.5 percent of all of the oil produced in Texas will come from projects in which fluids are being injected into the reservoirs. Within the next 15 years it is indicated that from one-third to one-half of the oil produced in Texas will come from fluid injection projects including thermal recovery, so there can be no argument as to their growing importance. It should be noted that this growth is due in part to the fact that the production from many secondary projects falls within the marginal well allowable, and for that reason is not prorated. Thus, there is a definite incentive in Texas to apply fluid injection methods extensively.

In recent years, much attention has been devoted to the application of heat to reservoirs which contain low-gravity, high-viscosity crude oil. Much of the reserves of heavy, viscous oil occur at shallow depths where it is not practical to apply sufficient fluid pressure to the reservoir to displace the oil effectively on account of poor mobility relations. Heating the oil in the reservoir, either by underground ignition and the combustion of part of the oil content as fuel, or by the injection of hot fluids, such as hot water or steam, serves to reduce the viscosity of the oil and thereby improve its mobility. Thermal methods are gaining wide acceptance for the recovery of heavy oil reserves and they will be of significant importance in Texas in the future, although, proportionately perhaps, of lesser magnitude than in certain other states that possess larger reserves of heavy crude oil.

It should be noted, however, in this connection that consideration is being given to the use of the underground combustion process in the place of water injection for the recovery of lighter crude oil in areas where adequate supplies of water are not available. There is not complete agreement among the companies most experienced in thermal operations as to the feasibility of such substitution, although it is known that the percent of the oil content of the reservoir required for fuel increases with increased crude oil gravity, thereby reducing the efficiency of the recovery process. Nevertheless, even though it is not possible to predict when or to what extent the combustion process may take the place of conventional water injection, the prospect of its more widespread use should not be underestimated because of the profound effect it could have on the amount of water that, otherwise, will be required for the production of oil.

PROCEDURE FOR THE STUDY

The writer directed five biennial studies of United States oil resources for the Interstate Oil Compact Commission. Subsequently, he collaborated in the preparation of a report on "World Oil Resources" for the Sixth World Petroleum Congress. These several studies have given him some measure of familiarity with methods for the estimation of oil reserves which, as stated previously, are fundamental to an estimation of future water requirements for the production of oil.

The Compact's studies of the United States oil resources were discontinued in 1962 because of inablility to obtain accurate information on Texas oil resources. Thus, the Water Development Board and, in turn, the writer were faced with a formidable problem in the development of information on what the future requirements for water in the production of oil in Texas might be, in a limited period of time.

Initially, it was proposed that an attempt be made to revise and update the excellent and comprehensive report of the Texas Petroleum Research Committee, "Oil Resources of Texas, 1954," by Fancher, Whiting, and Cretsinger. After consultation with Professor Whiting, a co-author of this report who is presently serving as Director of Texas Petroleum Research Committee in addition to his duties as Chairman of the Department of Petroleum Engineering at Texas A & M University, this plan was abandoned because of lack of time and money and because competent personnel to assemble and classify the great mass of statistical information were not immediately available.

The writer and Mr. Harold D. Holloway, of the Board's technical staff, then consulted with Mr. Morgan J. Davis, formerly Chairman of Humble Oil and Refining Company, a petroleum geologist of international repute who has devoted much attention to the evaluation of oil and gas reserves and future productive capacity, and who is a recognized authority on these subjects. Mr. Davis' opinion was solicited as to whether assistance might be obtained from the American Petroleum Institute which would permit the utilization of its basic reserve data on individual Texas fields. Mr. Davis offered little encouragement on the possibility of securing API figures. He expressed the opinion that a largely mathematical projection, based on such information as was readily available, was about all that could be done in a few months time.

Since it did not appear to be possible to secure oil reserve information from other sources within the limited period of time available, the writer was compelled to follow Mr. Davis' suggestion to attempt an estimation of future water requirements based on mathematical projections. These projections have been supplemented by other information available to the writer which will be referred to in following sections of the report.

Mention should be made of a recent report, "Methods of Estimating Reserves of Crude Oil, Natural Gas, and Natural Gas Liquids," by Wallace F. Lovejoy, Professor of Economics, and Paul T. Homan, Research Associate and former Director of Graduate Studies in Economics, at Southern Methodist University, and published by Resources for the Future, Inc., in 1965. Dr. Lovejoy's and Dr. Homan's scholarly study is first class, and it has served as a valuable guide to the writer as he has been confronted with obviously difficult problems and with only very limited time in which to attempt to solve them. The writer believes that it is the best consideration of methods employed for estimating oil reserves that has ever come to his attention. The results of this study will very likely have a profound effect on future estimations of hydrocarbon reserves.

ESTIMATION OF TEXAS OIL RESOURCES

From the results of previous studies along with recent studies of the discovery of oil reserves, the oil resources of Texas in known reservoirs as of January 1, 1965, are estimated as follows:

		Millions of Barrels
(1)	Estimation of Original Oil Content of Reservoirs......	130,415
(2)	Total Oil Production to January 1, 1965	27,269
(3)	Estimated Primary Oil Reserves........................	14,943
(4)	Estimated Additional Recovery by Conventional Fluid Injection Methods Under Economic Conditions Existing as of January 1, 1965........................	4,771
	Item (3) plus Item (4): Total Estimated Reserves..	19,714
(5)	Part of Item (4): Reserves Recoverable by Water Injection..	4,060

As of January 1, 1965, the oil recovery efficiency from Texas oil fields amounted to 36.03 percent of the total oil in place. This figure represents the relation that past production plus primary and fluid injection reserves bears to the original oil content of the State's reservoirs. It is slightly better than the national average, which was calculated in the Fifth Biennial Report, as of January 1, 1962, to be 33.6 percent of the total oil in place.

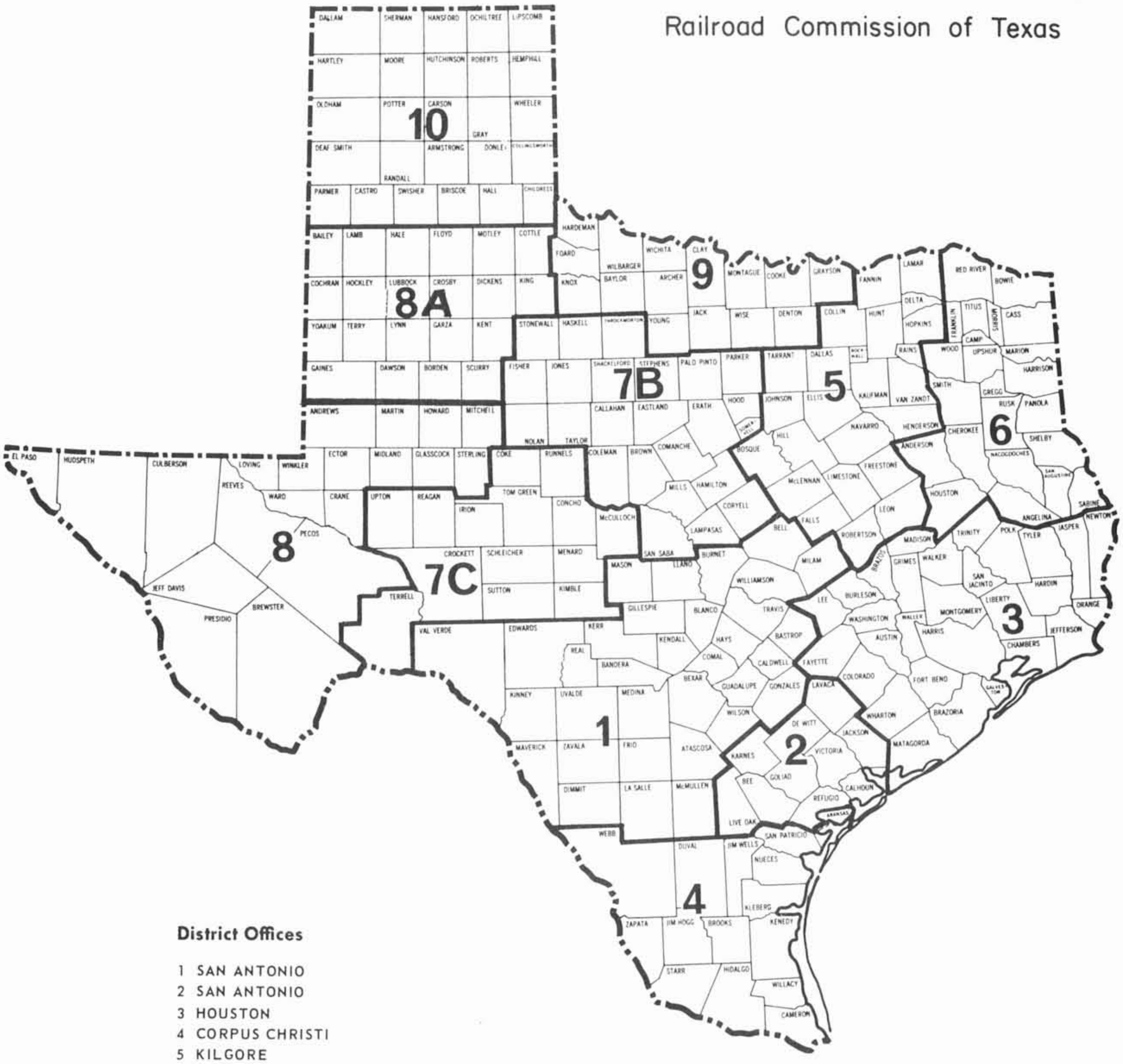
ESTIMATION OF OIL RESERVES RECOVERABLE BY WATER INJECTION IN TEXAS RAILROAD COMMISSION DISTRICTS

The estimated oil reserves of Texas recoverable by water injection as of January 1, 1965 (Item 5 of the preceding schedule) are located in the respective Railroad Commission Districts* as follows:

District	Percent of Total	Millions of Barrels
1	1.14	46.3
2	0.48	19.5
3	2.36	95.8
4	4.24	172.1
5	0.59	23.9
6	6.26	254.2
7B	5.96	242.0
7C	1.98	80.4
8	61.26	2,487.2
9	13.43	545.2
10	2.30	93.4
	Total	4,060.0

* For convenient reference the Railroad Commission Districts are shown on Figure 1. While this report was in process of preparation District 8 was divided into two new districts: District 8 (restricted) and District 8A. Since information used in this report comes from District 8 as it was originally constituted, it is not feasible to separate the data so as to conform to the boundaries of the new districts.

Figure I
Oil and Gas Division
Railroad Commission of Texas



District Offices

1 SAN ANTONIO
2 SAN ANTONIO
3 HOUSTON
4 CORPUS CHRISTI
5 KILGORE
6 KILGORE
7B ABILENE
7C SAN ANGELO
8 MIDLAND
8A LUBBOCK
9 WICHITA FALLS
10 PAMPA

These district reserves have been calculated on the basis of past production experience. It is realized that such determination is questionable, but no alternative method is available at this time.

From the preceding tabulation, and by reference to Figure 1, it will be evident that North Texas and West Texas contain a great part of the oil reserves recoverable by water injection. As mentioned previously, these are the parts of the State which, in general, are most deficient in water resources.

ESTIMATION OF OIL RESERVES BY WATER INJECTION FROM FUTURE DISCOVERIES IN TEXAS

The oil reserves of Texas recoverable by water injection, listed in the preceding sections, do not include oil that will be discovered in future years and which for that reason is not available at the present time. Since the projection of water requirements for the State by the Water Development Board is to extend through the year 2020, consideration must be given to the additional oil that will be found in Texas in future years and to that part of future discoveries which can be produced as a result of the injection of water into the reservoirs of new fields.

In order to determine what the reserves of oil recoverable by water injection from future discoveries in Texas might be, the writer has employed in somewhat modified form a method developed by C. L. Moore. (See Chart F, page 24 of "Method for Evaluating U.S. Crude Oil Resources and Projecting Crude Oil Availability," U.S. Department of the Interior, Office of Oil and Gas, May, 1962.) In adopting the Moore procedure it has been necessary, as discussed previously, to assume a continuation of economic conditions as of January 1, 1965. Also it has been assumed, as indicated by previous Compact studies, that the percent of future discoveries which will be produced in Texas as a result of fluid injection will increase from 25 percent of total production in 1960 to 50 percent in 2020, and that 85 percent of the oil produced by fluid injection will be by water injection.

During the period when the Compact's studies of United States oil resources were being made, from 1952 through 1962, it was shown that reserves developed by new oil discoveries in Texas amounted consistently to around 32 percent of the new reserves found in the United States, the exact average figure for this period being 32.1 percent. This percentage factor has been applied to the projection by the use of Chart F of the reserves that will be developed by future discoveries in the United States, and the resulting figures for successive time periods have then been further modified by applying the following factors:

1. Increasing factors representing the percent of new discoveries which will be produced by fluid injection.

2. A factor based on past experience of the amount of fluid injection oil that will be produced by water injection.

These calculations provide the following figures for additional water injection reserves in Texas from new discoveries for succeeding future periods:

Period	Number of Years		Millions of Barrels
1965-70	6		1,310
1971-80	10		2,817
1981-90	10		2,374
1991-2000	10		2,087
2001-10	10		1,814
2011-20	10		1,569
		Total	11,971

The manner in which calculations have been made, from which these figures have been derived, is given in Appendix A.

In the preceding section of this report it is shown that the estimated oil reserves in Texas susceptible to recovery by water injection as of January 1, 1965 are 4,060 million barrels. Adding this figure to the reserve figure from future discoveries in the preceding tabulation will give a total reserve of 16,031 million barrels susceptible to recovery by water injection in Texas from 1965 to 2020 inclusive.

Before concluding this discussion, it is proper to comment that the assumptions on which the writer's calculations have been based are certainly not the only ones which could be made, such as the possibility that recovery by underground combustion may be substitued for water injection in future years, thereby reducing water requirements. Such an assumption, as discussed previously, can be supported by seemingly logical explanation, and, as can be expected, will yield entirely different numbers. It is for this reason that a great deal of attention has been given in the following section to an attempt to verify the reserve figures developed by a special adaptation of the Moore method of projecting future discoveries to Texas conditions.

VERIFICATION OF ESTIMATION OF FUTURE OIL RESERVES

Although the writer has much respect for Mr. Moore's ability and for the great amount of time and effort that has been devoted to his studies, it is realized that projections of reserves and of future production for extended periods must be, by necessity, arbitrarily defined. The hazards and uncertainties of such projections are inherent to them and have already been emphasized. Therefore, an effort was made to develop a way whereby figures derived from use of Moore's Chart F could be tested and verified.

In 1956 the Chase Manhattan Bank published a report, "Future Growth and Financial Requirements of the World Petroleum Industry," by Joseph E. Pogue and Kenneth E. Hill. This report devoted special attention to the future production of oil in the United States, and a graph was included in it which shows a predicted pattern of annual oil production in the United States through the year 2035. This graph has proved to be quite accurate through the year 1964, if consideration is given to the effect of increased imports of crude oil from foreign countries.

Albert E. Sweeney, Jr., used the trend of production shown in the Pogue and Hill graph to estimate the "Future Magnitude of Secondary Recovery in the United States" in a paper presented at the 26th Annual Meeting of North Texas Oil and Gas Association, Wichita Falls, Texas, March 24, 1956. The paralleling curve developed by Mr. Sweeney in this paper has proved to be even more accurate than its model, because the production of secondary oil in the United States to a large extent is not prorated. Since the Sweeney curve has proved to be a reliable criterion for the amount of secondary production in the United States for the period from 1955 through 1964, it has been widely accepted by the oil industry and by agencies of state and federal government. Because of its proven reliability, it was concluded that the same trend could be applied to Texas since it has been shown by the several Compact studies that the percent of oil produced in Texas by water injection in relation to the total oil produced by such methods in the entire United States has remained reasonably constant during the period in which these studies were made.

In the Compact's Fifth Biennial Report it is shown that Texas produced 224,401,290 barrels of oil in 1960 by all forms of fluid injection. Of this total, approximately 180,900,000 barrels of oil was produced by water injection. Unfortunately, this is the most recent figure available to the writer, so it must be used as the starting point for a future projection of production based on a curve with a paralleling trend to the curve developed by Mr. Sweeney. Using this method of projection it is indicated that oil production by water injection in Texas in 1965 in round numbers should be 275 million barrels. Considering the known growth in water injection projects in the State since 1960, this figure appears to be reasonable.

Proceeding from the point on the paralleling curve for Texas where its oil production by water injection in 1960 is located, the State's oil production by water injection for successive time periods has been calculated by adding progressively the production for each year into groups of 10 years duration as indicated by the curve. This procedure then gives the following figures:

Period	Number of Years		Millions of Barrels
1965-70	6		1,995
1971-80	10		5,390
1981-90	10		4,370
1991-2000	10		2,357
2001-10	10		1,250
2011-20	10		650
		Total	16,012

One will note at once that the total figure in this tabulation corresponds quite closely to the total reserve figure by water injection developed in the preceding section. This similarity under most circumstances would be little more than a coincidence, for it obviously is not reasonable to compare directly the status of future reserves with future production. However, it may be anticipated that as the rate of discovery of new fields declines in future years, affecting, as it will, the rate of primary production, available secondary reserves will be required to make up the deficiency. Thus, it may be anticipated that secondary reserves will be produced more rapidly in the future and approximately at the rate of their discovery. For that reason, the comparison which has just been made between reserves and production is considered to possess some measure of verisimilitude.

The estimated annual production of oil by water injection based on the adaptation of the Sweeney graph is given in Appendix B.

CALCULATION OF AMOUNT OF WATER REQUIRED FOR PRODUCTION OF OIL IN TEXAS

In the preceding sections the present and future oil reserves of Texas susceptible to recovery by water injection and the rate at which they probably can be produced have been estimated as accurately as available information will permit. After the calculations in the preceding two sections had been completed, the information on reserves and production could then be used as the basis for further calculations of the water that will be required to produce them. Fortunately, calculations of the amount of water required for the production of oil are more precise than the preceding reserve estimations because much more reliable information is available on the past performance of water injection projects in Texas.

The most recent information on the amount of water required for the production of oil in Texas is contained in Bulletin 62 of the Texas Petroleum Research Committee, "A Survey of Secondary Recovery and Pressure Maintenance Operations in Texas to 1962." This bulletin contains information on 1,696 secondary and pressure maintenance projects in Texas of which 1,132 were commenced before January 1, 1960. The information in Bulletin 62 on each of these 1,132 projects has been reviewed in order to eliminate from further consideration strictly gas injection projects and combination gas and water injection projects, it being the desire to select projects for use in this report on which the following information was completely available:

1. Total oil production since the commencement of water injection.

2. The percent of the total oil production due to the injection of water.

3. The total amount of water injected since the commencement of operations.

Projects on which all of the desired information was not available were eliminated from further consideration. Also, projects which had not been in operation for at least 2 years were eliminated. Out of the 1,132 projects included in Bulletin 62, it was found that complete information on 629 projects was available. Information on each of these 629 projects was tabulated, and a summary of the information is listed in Table 1 by Railroad Commission Districts and for the State as a whole.

From Table 1 it can be seen that an average of 8.2 barrels of water is required to produce 1 barrel of oil in Texas.

The small amount of water required to produce 1 barrel of oil in District 6 is due, so it is believed, to the fact that practically all of the operations in this district are pressure maintenance projects in fields of fairly recent discovery, which are characterized by economical use of water.

The large amount of water required to produce 1 barrel of oil in District 4 is due to large gas caps which are commonly found in the oil fields which produce from the Frio and Jackson formations in this district. Much water has been required to fill depleted gas caps in District 4.

Figures from the other districts are considered to be representative. Variations in the amount of water required to produce 1 barrel of oil can be attributed to the fact that successful, mediocre, and unsuccessful projects have been included with no intention to favor any one group. This is correct procedure, although, possibly, greater emphasis should be placed on the unsuccessful projects, which usually consume large quantities of water and produce only minor quantities of oil, and because many of the better secondary prospects in the State have already been developed leaving a greater percentage of mediocre and inferior prospects for development in the future.

There are, of course, factors of somewhat similar importance which may tend to minimize the future use of water in the production of oil. One of these, the possible substitution of underground combustion for water injection, has already been considered. Another important factor is the trend toward unitization early in the life of fields that will facilitate the installation of field-wide pressure maintenance projects which are economical in the use of water both at the beginning and during advanced stages of their operation. As portions of the field become depleted, produced water can be used for injection along the advancing flood front in the reservoir, and by this process water can be reused several times thereby serving in large part to eliminate the necessity of drawing on some supplemental and possibly extraneous supply for make-up water. After the unitized field becomes completely depleted of its recoverable oil, it might then become a source of supplemental water for nearby fields. By such means income from the sale of water, in addition to the return from the sale of oil, might be realized from wells producing with a high water-oil ratio, and by such disposition of water it might be possible to produce some oil which otherwise could not be recovered profitably.

It is possible that these various factors, some of which will influence the use of large quantities of water and others which will tend to reduce water requirements, will tend to balance each other. Unfortunately, it is not possible at this time to predict what their long-range effects may be. For that reason, the figures developed in Table 1 are considered to be about as good as could be obtained at the time this report was written, and, therefore, they have been adopted for use in estimating the amount of water that will be required in Texas in future years for the production of oil.

VERIFICATION OF WATER REQUIREMENTS FOR PRODUCTION OF OIL IN TEXAS

As mentioned in the preceding section, the projects included in Table 1 had been in operation for at least 2 years. However, many had not been nearly depleted when statistics from them were included in Bulletin 62. Therefore, as a check on the reliability of the average figures from this table, data were tabulated on several selected projects on which the writer has personal knowledge, all of which have produced at least 80 percent of their estimated oil recovery. Data on these selected projects are listed in Table 2.

The figures in Table 2 purposely have not been averaged because the individual projects are insufficient in number to give representative average figures. Nevertheless, it can be observed by visual inspection that the actual amount of water used to produce oil conforms reasonably well with the average figures in Table 1 for the respective Districts. It should be noted that some of the projects in Table 2 are considered to be highly successful, and, usually, the successful projects require less water to produce oil than do mediocre and inferior projects.

CALCULATION OF MAKE-UP WATER IN EXCESS OF PRODUCED FORMATION WATER REQUIRED FOR THE PRODUCTION OF OIL IN RAILROAD COMMISSION DISTRICTS OF TEXAS

The availability of water is essential for the commencement of an injection project. The water that is needed to commence a secondary project may be available in the field from the same oil-bearing formation into which water is to be injected, but usually the volume of produced water from this source is insufficient for the requirements of the project so that a supplemental supply is required. This is particularly true during the early life of a project when voids in the producing formation, from which oil and gas have been withdrawn previously, must be filled with liquid in order to build up the desired pressure in the reservoir. Consequently, the Water Development Board will be concerned primarily with the amount of make-up water, in addition to produced water, which will be required from other sources in future years in Texas for the production of oil.

Fortunately, what is considered to be reliable information on the volume of make-up water used in water injection projects in Texas has been compiled by the Board's technical staff from various reports of Texas Petroleum Research Committee and was made available to the writer. Statistics for the various Railroad Commission Districts for the years of 1958, 1959, 1960, and 1961 were selected as being representative and were combined in Table 3.

It can be seen from Table 3 how the percentage of make-up water has been calculated. These percentage factors can then be applied, as has been done in Table 4, to determine the amount of make-up water that will be required for injection projects in future years.

Near the beginning of this report it is stated that "No attempt has been made to determine the availability of water for the production of oil." Specifically this is correct, but it could be helpful to mention briefly and without detailed discussion some possible sources of make-up water in addition to underground aquifers. Some possible sources are listed as follows:

1. The use of sea water in coastal fields, and in offshore fields such as is being done successfully in California and Louisiana.

2. The use of industrial and sanitary effluent, which is already being used in West Texas, and has been widely used in Illinois, after treatment for the elimination of microorganisms which would plug input wells.

3. The use of concentrated brines from municipal water-treating plants, which will be considered in a later section of this report.

In considering past experience in the use of water for the production of oil in Texas, it is evident that there are many instances where little effort has been made to use water efficiently. The State's conservation laws and regulations have provided an incentive for oil recovery efficiency. Similarly, it appears desirable that they should be so directed that water will be used without waste, particularly in parts of the State where water is a scarce resource.

PROJECTION OF FUTURE WATER REQUIREMENTS FOR PRODUCTION OF OIL IN TEXAS

Having made an estimate of the amount of oil that will be produced by water injection in future successive time periods in Texas and in the respective Railroad Commission Districts, and the total amount of water that has been used to produce oil and the part of the total which is make-up water, the estimation of future water requirements is based on a simple mathematical calculation. This information is given in Table 4, in which figures derived from the modified Sweeney graph, which are listed in Appendix B, have been used.

In order that there may be no misunderstanding, it is mentioned again that all of these calculations implicitly assume that the pattern of oil discovery in the future will conform to the figures developed from the Moore Chart F. However, if major oil discoveries in the future will be in offshore areas, as many authorities believe will be the case, it can be understood that water requirements could be entirely different. It is regretted that there seems to be no plausible way whereby the course of future oil discovery can be predicted with greater accuracy.

In order to simplify the use of the figures in Table 4, they have been broken down in Table 5. Table 5 is in nine sections, which are listed as follows:

1. Estimation of Texas Oil Production by Water Injection from 1965 to 2020 Inclusive.

2. Estimation of Total Water Required for the Production of Oil in Texas from 1965 to 2020 Inclusive.

3. Estimation of Total Water Required from Other Sources for the Production of Oil in Texas from 1965 to 2020 Inclusive.

4. Estimation of Oil Production by Water Injection in Each Texas Railroad Commission District in Successive Time Periods from 1965 to 2020 Inclusive.

5. Estimation of Total Oil Production by Water Injection in Each Texas Railroad Commission District from 1965 to 2020 Inclusive.

6. Estimation of Total Water Required for the Production of Oil in Each Texas Railroad Commission District in Successive Time Periods from 1965 to 2020 Inclusive.

7. Estimation of Total Water Required for the Production of Oil in Each Texas Railroad Commission District from 1965 to 2020 Inclusive.

8. Estimation of Total Water Required from Other Sources for the Production of Oil in Each Texas Railroad Commission District for Successive Time Periods from 1965 to 2020 Inclusive.

9. Estimation of Total Water Required from Other Sources for the Production of Oil in Each Texas Railroad Commission District from 1965 to 2020 Inclusive.

It is believed that the information presented in Tables 4 and 5 can be understood readily, and that no further explanation is required.

WATER REQUIREMENTS FOR THERMAL RECOVERY

In the Fifth Biennial Report on United States oil resources it is stated that Texas had oil reserves of 11,081 million barrels that were physically recoverable by newer methods of production. It cannot be established precisely how much of this additional recovery might be produced profitably as of January 1, 1965. Also, it is not possible to segregate exactly the total estimated recovery as to the different methods, but, as the Fifth Biennial Report indicates, thermal methods of recovery, unquestionably, received important consideration, although estimations of recovery by application of the newer methods were reduced rather drastically from the figures given in the Fourth Biennial Report because of disappointing results from various miscible projects.

As stated previously, interest in thermal recovery and the number of thermal projects in operation have increased substantially in recent years, and since one of the thermal methods involves the injection of steam into reservoirs containing heavy, high-viscosity crude oil, the amount of water required for the generation of steam in future years will be of interest to the Water Development Board similar to its interest in the amount of water required for conventional injection into the oil reservoirs of the State's fields.

It is regretted that application of thermal methods in Texas is so recent that it is not possible to develop reliable figures on the amount of water, converted to steam, that is required to produce 1 barrel of oil, such as could be done for conventional water injection operations. Thus, it has been necessary to depend on information obtained from California which was secured by the writer in 1964 and 1965 in a study of these operations, and which has been verified recently in consultation with the research department of a company which has been one of the pioneers in the development and application of thermal methods. It has been found that the average oil reservoir can be heated adequately by the injection of 1.6 pore volumes of water converted to dry steam and, on the average, such heating will recover 57 percent of oil in place in the reservoir.

From the preceding figures, it is, therefore, possible to estimate the water requirements and the recoverable reserves of heavy oil in Texas fields by combining them with other physical characteristics of oil reservoirs that are commonly employed in the estimation of oil reserves, such as: area of the reservoir, average reservoir thickness, average porosity, and average oil saturation. Such information was obtained on the oil fields of Texas from Volume XXXIV, Part II, of the 1964 Year Book of the International Oil Scouts Association, pages 316-684, and from other records, reports, and statistics in the writer's possession.

In using information from the 1964 Year Book it was decided arbitrarily to include only fields which produce 20° API or heavier crude oil. It was found that there were 217 fields in the State in this classification, and information on them has been consolidated by Railroad Commission Districts and is presented in Table 6.

Since no trend of thermal production has been established in Texas, there is no feasible way in which water requirements can be segregated into successive time periods, as has been done for the requirements for conventional water injection operations, as listed in Tables 4 and 5. Furthermore, the problem is even more complicated by the fact that no one can predict at the present time how much of the reserve of heavy oil will be produced by underground combustion and how much will be produced by the injection of steam even though much interest is manifest in applications of the combustion process. Since many of the fields which produce heavy oil are of small size, the writer believes that it will prove to be more practical to use the steam injection process for a large part of the Texas reserve, but this is an opinion which cannot be confirmed by existing experience, although it is known that fairly large fields and fairly large reserves are required for underground combustion in order that the large compressor facilities, required to maintain the fire-front in the reservoir, can be used over an extended period of time. Thus, development for in situ combustion projects has been planned for periodic expansion in as many as 20 increments.

In great contrast to the future requirements for water in conventional secondary recovery and pressure maintenance operations, much of the indicated reserves from thermal recovery are located in East Texas, in the Gulf Coast, and in South Texas where water resources generally are more abundant. In District 7C about 95 percent of the reserve of heavy oil is in the Olson field of Crockett County. Around 97 percent of the reserve of heavy oil in District 8 is in the Tucker field of Crane County. Thus, if these two fields were eliminated from consideration, there would be only minor reserves of heavy oil in West Texas, and none in the Panhandle, which might require water for the generation of steam.

It will be noted that the estimated total water requirements for the generation of steam of about 10.5 billion barrels (Table 6) are only about 9 percent of the total estimated requirements for make-up water for conventional water injection (Table 5, part 3). However, water of high quality and free from mineral salts is required for the efficient operation of steam generators, so the water that will be required for thermal recovery may encroach on other industrial uses.

It should be noted that the U.S. Bureau of Mines considers that oil possessing a gravity of 25° API or less is suitable for the application of thermal recovery by steam injection. The reason why this higher figure was not used in this report, to define the fields in Texas that are considered to be thermal prospects, is because a large majority of the projects so far considered to be successful are located in California fields where the oil gravity is 20° API or less. California experience, therefore, has had to be the principal criterion available for defining the number of Texas thermal prospects. However, when the list of selected fields was being compiled from the 1964 Oil Scouts Year Book it was noted that there were 757 fields in Texas that produced crude oil having an API gravity of 20° to 25°. Thus, if this large number of fields should be included with the 217 considered in Table 6, it is not hard to understand how a recoverable reserve in the range of 11 billion barrels of oil might be predicted, as was done in the Compact's Fifth Biennial Report.

DISPOSAL OF WASTE WATER FROM MUNICIPAL TREATING PLANTS
IN WATER INJECTION PROJECTS

The writer is advised by the Board that Southwest Research Institute has recommended a study of the possibilities for improving the quality of the municipal water supply in 37 Texas cities and towns. All processes in common use for the removal of mineral salts from water produce as a by-product a concentrated brine for which some disposition must be provided in order to prevent contamination of surface water and the destruction of vegetation with which it may come in contact. An ideal way to dispose of the waste brine from a purification plant would be to use it for injection into oil reservoirs to increase recovery, as has been mentioned previously. Fortuitously, some of the municipalities recommended for study by Southwest Research Institute are located in counties where there are oil fields within reasonable proximity to them and in which water injection projects are already in operation or which possess favorable possibilities for successful water injection.

It is suggested, as plans are advanced for the improvement of water quality in various places, that consideration be given to the disposal of waste water in the nearby oil fields listed in the following schedule:

City	County	Oil Field that Might be Used for Disposal of Water
Burkburnett	Wichita	Numerous fields referred to only as Wichita County Regular
Corpus Christi	Nueces	Minnie Bock, Red Fish Reef
Fort Stockton	Pecos	Fort Stockton, Lehn Apco, Pecos Valley
Freer	Duval	Colmena, Lundell, Loma Novia, Government Wells
Hebbronville	Jim Hogg	Colorado, El Javali
Kingsville	Kleberg	Seeligson, Stratton
Karnes City and Kenedy	Karnes	Falls City, Porter
Midland	Midland	Spraberry
Monahans	Ward	South Ward, Ward-Estes, Emperor, Weiner-Colby
Premont	Jim Wells	La Gloria
Refugio	Refugio	Tom O'Connor
Rio Grande City	Starr	Marks, Ricaby

Very likely there may be other fields in the counties listed which can provide facilities for the disposal of waste water from treating plants. Similarly, there may be fields in other counties, with which the writer is not familiar, that can provide such facilities for several other municipalities in the list of places recommended by Southwest Research Institute. The writer has some knowledge of all of the fields listed in the preceding schedule and it is believed that most of them are of such size that they could accomodate substantial quantities of waste water. It is for these reasons that they have been listed.

Before deciding on the disposal of waste water into oil reservoirs, it will be necessary to determine whether the water to be injected is compatible with water indigenous to the oil-bearing formation. If the waters are not compatible, it will be necessary to treat the waste water so that insoluble compounds will not be formed at the bottom of the input well or in the reservoir thereby restricting or preventing continued injection.

There is, of course, an economic limit to the distance that water can be moved to be injected into an oil reservoir. The quantity of water available and the certainty of a continuous supply will have an economic bearing on the distance water can be transported. However, wherever a serious disposal problem may develop it may be economic to move water by tank truck even though it is not feasible to transport it by pipeline.

The town of Freer, in Duval County, is considered to be an excellent prospect for the disposal of waste water into oil reservoirs, for it is located in portions of the Loma Novia and Government Wells fields, in both of which large water injection projects are in operation. Thus, it would not require an extensive pipeline connection to move waste water from a treating plant in or adjacent to the town to water distribution systems in the fields.

RECOMMENDATIONS

It should be evident from the preceding discussion that any factual study on the amount of water required in the future for the production of oil must be based on a knowledge of the amount of oil available for recovery. Such knowledge can be gained only by a study of oil reserves susceptible to recovery by water or steam injection preferably by individual fields.

Since it does not appear to be possible to secure up-to-date reserve information from other sources, the only alternate method to provide the Water Development Board with more precise information on oil reserves and, in turn, on water requirements for the production of oil, is to arrange to revise and bring up-to-date the report of Texas Petroleum Research Committee on "Oil Resources of Texas, 1954" previously referred to. This is not a small undertaking, as Professor Whiting has clearly explained, but it is evident that every year the work of revision is delayed will make it just that much more laborious and difficult to accomplish.

The writer is very much aware of the deficiencies in the studies on which this report is based and the hope can be expressed that they can be eliminated in the future. However, as Mr. Davis has pointed out, the procedure that has been employed has been about the only way that this report could have been prepared within the limited time that has been available.

There would seem to be impressive opportunities for cooperation between the Water Development Board and the Railroad Commission on the assembly of information on the volume of water being used for the production of oil. Such cooperation should assure that both State agencies obtain information essential to their business, and at the same time the oil industry would be freed of the necessity of compiling multiple forms and reports.

It is greatly to the advantage of the government of Texas and to the people of Texas that improved oil recovery technology should be applied extensively in the State. In order for this to be done, adequate supplies of water must be available for the operation of the many existing and future water injection operations in the State. An obvious way to assure that adequate supplies will be available is for the Board to be informed in advance what the future requirements will be in order for it to plan accordingly. Likewise, it is to the advantage of the oil industry to cooperate with the Water Development Board for, otherwise, production operations might have to be curtailed in future time by a lack of water in parts of the State where water, even of poor quality, is a scarce commodity. Some form of control to prevent extravagant waste of water appears to be desirable.

Although API reserve figures were not available for this study, it should be understood that the API figures do not represent a prediction of probable or possible future discoveries, which could be used for the projection of a trend of production into future years. Rather, these figures represent a working inventory of the amount of oil immediately available in the Nation. As such they have value for the purpose for which they are developed, but from the standpoint of the information desired by the Water Development Board, API reserve figures, even if broken down to an individual field basis, would be inadequate unless they were accompanied by basic information on the characteristics and oil content of the reservoirs and on the mechanics of primary production performance.

In contrast, the reserve data developed under the writer's direction for the Interstate Oil Compact Commission has had much more practical value because reserves susceptible to recovery by improved technology are considered and because the figures developed for the five consecutive biennial reports permit a direct measurement of the efficiency of oil recovery in the various producing states and for the Nation as a whole.

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Professor R. L. Whiting, of Texas A & M University, has been of great assistance to the writer, particularly in his effort to evaluate the possible impact of thermal recovery methods on future production of oil in Texas.

Professor Wallace F. Lovejoy, of Southern Methodist University, reviewed a preliminary draft of the report in great detail. His comments were most helpful in defining the limitations of the several assumptions which had to be made as a basis for the calculations employed for projections of future oil production and water requirements.

Mr. Morgan J. Davis, petroleum geologist and oil company executive, contributed time generously to a consideration of the various problems which confronted the writer in the preparation of this report and two ways in which they might be solved. The emphasis the writer has placed on improvements in the efficiency of use of water by pressure maintenance operations was at his suggestion.

Mr. C. L. Moore, of United States Department of the Interior, checked the writer's use of his Chart F for a projection of future discoveries of oil and the method which he employed to verify this projection. He encouraged the writer with his approval of what had been done. However, he expressed the belief that better methods for such projections were in process of development which, in the future, should remove some of the uncertainties that are inherent to the methods employed in this report.

The writer has worked directly under the supervision of Mr. Harold D. Holloway, Geologist for the Board. He has proved to be most helpful, and he has shown understanding of the multiple problems which have developed in the endeavor that has been made to complete this report within the period allowed. It has been pleasant to work with him.

The writer has found every member of the Board's staff and its executive officers with whom he has had contact to be much interested in the information to be developed by this report. Their desire to be helpful has been manifest in many ways, for all of which the writer is grateful.

Table 1.--Summary of calculations of amount of water required for production of oil in Texas

(All figures to January 1, 1962, in barrels of 42 U.S. gallons.)

Railroad Commission District	Number of projects included in calculation	Oil produced since start of projects	Oil produced by water injection	Total water injected in projects	Barrels of water used to produce 1 barrel of oil
1	4	2,166,893	1,688,165	19,786,695	11.7
2	3	1,592,494	968,132	5,150,968	5.3
3	5	8,831,176	4,005,996	38,009,542	9.5
4	14	7,445,819	5,669,346	92,405,071	16.3
5	11	5,503,024	4,803,692	39,399,724	8.2
6	11	32,044,765	26,138,834	73,948,971	2.8
7B	108	22,557,444	15,815,613	179,303,965	11.3
7C	15	7,335,098	5,453,035	63,724,599	11.7
8	164	208,199,633	174,254,256	1,276,441,280	7.3
9	292	83,423,799	66,477,845	722,232,620	10.8
10	2	296,903	194,615	3,820,532	12.8
Entire State	629	379,397,048	305,469,529	2,514,223,367	8.2

Table 2.--Information on oil produced and water injected for selected water injection projects in Texas

District	County	Field	Oil produced by water injection (barrels)	Total water injected in project (barrels)	Barrels of water used to produce 1 barrel of oil
1	La Salle	Washburn Ranch	135,495	1,576,972	11.6
2	Karnes	Falls City	722,142	3,449,000	4.7
4	Duval	Lopez*	1,825,484	41,948,055	23.0
	Webb	Mirando City	352,101	3,623,000	10.3
	Zapata	Escobas	92,255	1,050,515	11.4
	Duval	O'Hern	953,773	7,379,116	7.7
8	Ward	South Ward	800,753	7,174,965	8.9
	do	do	4,450,005	22,515,693	5.0
	Howard	Howard-Glasscock	3,485,000	18,546,023	5.3
	Pecos	Pecos Valley High Gravity	123,634	638,104	5.1
9	Archer	Webb	100,700	1,300,000	12.9
	do	Thomas	47,773	420,000	8.8
	do	Ferguson	54,011	505,682	9.3
	Eastland and Comanche	Kirk	888,348	8,325,000	9.4
	Montague	Hildreth	961,908	8,270,442	8.6
	Shackelford	Sedwick	121,000	940,000	7.8
	do	Hooker	102,215	1,300,000	12.7
	Throckmorton	Woodson	121,620	940,672	7.8

* Possesses a large, depleted gas cap.

Table 3.--Calculation of make-up water used in injection projects for all Railroad Commission Districts in 1958, 1959, 1960, and 1961

District	Total water used	Total produced water used	Total make-up water used	Percent of make-up water
1	11,484,259	715,756	10,768,503	93.8
2	8,537,323	1,787,497	6,749,826	79.1
3	71,237,407	19,193,320	52,044,087	73.0
4	198,466,322	96,112,759	102,353,563	51.6
5	23,285,827	1,355,521	21,930,306	94.2
6	718,250,634	672,483,973	45,766,661	6.4
7B	221,891,622	15,071,015	206,820,607	93.2
7C	140,409,686	29,062,417	111,347,269	79.3
8	1,299,004,109	76,155,102	1,222,848,917	94.2
9	681,570,305	67,970,012	613,600,293	90.0
10	51,345,002	291,135	51,053,867	99.4

Table 4.--Calculation of future requirements of water for production of oil in Texas

(All volumetric figures in millions of barrels of 42 U.S. gallons.)

Column numbers are identified below table.

Railroad Commission District	1965-70					1971-80					1981-90				
	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
1	22.7	11.7	265.6	93.8	249.1	61.4	11.7	718.4	93.8	574.7	49.8	11.7	582.7	93.8	546.6
2	9.6	5.3	50.9	79.1	40.3	25.9	5.3	137.3	79.1	108.6	21.0	5.3	111.3	79.1	88.0
3	47.1	9.5	447.4	73.0	326.6	127.2	9.5	1,208.4	73.0	882.1	103.1	9.5	979.5	73.0	715.0
4	84.6	16.3	1,379.0	51.6	711.6	228.5	16.3	3,724.5	51.6	1,921.8	185.3	16.3	3,020.4	51.6	1,558.5
5	11.8	8.2	96.8	94.2	91.2	31.8	8.2	260.8	94.2	245.7	25.8	8.2	211.6	94.2	199.3
6	124.9	2.8	349.7	6.4	22.4	337.4	2.8	944.7	6.4	60.5	273.6	2.8	766.1	6.4	49.0
7B	118.9	11.3	1,343.6	93.2	1,252.2	321.3	11.3	3,630.7	93.2	3,383.8	260.4	11.3	2,942.5	93.2	2,742.4
7C	39.5	11.7	462.1	79.3	366.4	106.7	11.7	1,248.4	79.3	990.0	86.5	11.7	1,012.0	79.3	802.5
8	1,222.1	7.3	8,921.3	94.2	8,403.9	3,301.9	7.3	24,103.9	94.2	22,705.9	2,677.1	7.3	19,542.8	94.2	18,409.3
9	267.9	10.8	2,893.3	90.0	2,604.0	723.9	10.8	7,818.1	90.0	7,036.3	586.9	10.8	6,338.5	90.0	5,704.6
10	45.9	12.8	587.5	99.4	584.0	124.0	12.8	1,587.2	99.4	1,577.7	100.5	12.8	1,286.4	99.4	1,278.7
Total for the period	1,995.0	--	16,797.2	--	14,651.7	5,390.0	--	45,382.4	--	39,487.1	4,370.0	--	36,793.8	--	32.093.9

Identification of Column Numbers

(1) Estimated oil production by water injection during period.
(2) Barrels of water required to produce 1 barrel of oil.
(3) Total water required (Column 1 x Column 2).
(4) Percent of water used from other sources in addition to produced formation water.
(5) Requirements of water from other sources $\left(\text{Column 3} \times \frac{\text{Column 4}}{100}\right)$.

Table 4.--Calculation of future requirements of water for production of oil in Texas--Continued

Railroad Commission District	1991-2000					2001-10					2011-20				
	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
1	26.9	11.7	314.7	93.8	295.2	14.3	11.7	167.3	93.8	156.9	7.4	11.7	86.6	93.8	81.2
2	11.3	5.3	59.9	79.1	47.4	6.0	5.3	31.8	79.1	25.2	3.1	5.3	16.4	79.1	13.0
3	55.6	9.5	528.2	73.0	385.6	29.5	9.5	280.2	73.0	204.5	15.3	9.5	145.3	73.0	106.1
4	99.9	16.3	1,628.4	51.6	840.3	53.0	16.3	863.9	51.6	445.8	27.6	16.3	449.9	51.6	232.1
5	13.9	8.2	114.0	94.2	107.4	7.4	8.2	60.7	94.2	57.2	3.8	8.2	31.2	94.2	29.4
6	147.5	2.8	413.0	6.4	26.4	78.2	2.8	219.0	6.4	14.0	40.7	2.8	114.0	6.4	7.3
7B	140.5	11.3	1,587.7	93.2	1,479.7	74.5	11.3	841.8	93.2	784.6	38.7	11.3	437.3	93.2	407.6
7C	46.7	11.7	546.4	79.3	433.3	24.8	11.7	290.2	79.3	230.1	12.9	11.7	150.9	79.3	119.7
8	1,443.9	7.3	10,540.5	94.2	9,929.2	765.7	7.3	5,589.6	94.2	5,265.4	398.2	7.3	2,906.9	94.2	2,738.3
9	316.5	10.8	3,418.2	90.0	3,076.4	167.9	10.8	1,813.3	90.0	1,632.0	87.3	10.8	942.8	90.0	848.5
10	54.3	12.8	695.0	99.4	690.8	28.7	12.8	367.4	99.4	362.5	15.0	12.8	192.0	99.4	190.8
Total for the period	2,357.0	--	19,846.0	--	17,311.7	1,250.0	--	10,525.2	--	9,180.9	650.0	--	5,473.3	--	4,774.0

Identification of Column Numbers

(1) Estimated oil production by water injection during period.
(2) Barrels of water required to produce 1 barrel of oil.
(3) Total water required (Column 1 x Column 2).
(4) Percent of water used from other sources in addition to produced formation water.
(5) Requirements of water from other sources $\left(\text{Column 3} \times \frac{\text{Column 4}}{100}\right)$.

Table 5.--Recapitulation of pertinent figures from Table 4

1. Estimation of Texas Oil Production by Water Injection from 1965 to 2020 Inclusive.

Period	Years	Millions of Barrels
1965-70	6	1,995.0
1971-80	10	5,390.0
1981-90	10	4,370.0
1991-2000	10	2,357.0
2001-10	10	1,250.0
2011-20	10	650.0
	Total	16,012.0

2. Estimation of Total Water Required for the Production of Oil in Texas from 1965 to 2020 Inclusive.

Period	Years	Millions of Barrels
1965-70	6	16,797.2
1971-80	10	45,382.4
1981-90	10	36,793.8
1991-2000	10	19,846.0
2001-10	10	10,525.0
2011-20	10	5,473.3
	Total	134,817.9

3. Estimation of Total Water Required from Other Sources for the Production of Oil in Texas from 1965 to 2020 Inclusive.

Period	Years	Millions of Barrels
1965-70	6	14,651.7
1971-80	10	39,487.1
1981-90	10	32,093.9
1991-2000	10	17,311.7
2001-10	10	9,180.9
2011-20	10	4,774.0
	Total	117,499.3

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

4. Estimation of Oil Production by Water Injection in Each Texas Railroad Commission District in Successive Time Periods from 1965 to 2020 Inclusive.

District 1

Period	Years	Millions of Barrels
1965-70	6	22.7
1971-80	10	61.4
1981-90	10	49.8
1991-2000	10	26.9
2001-10	10	14.3
2011-20	10	7.4
	Total	182.5

District 2

Period	Years	Millions of Barrels
1965-70	6	9.6
1971-80	10	25.9
1981-90	10	21.0
1991-2000	10	11.3
2001-10	10	6.0
2011-20	10	3.1
	Total	76.9

District 3

Period	Years	Millions of Barrels
1965-70	6	47.1
1971-80	10	127.2
1981-90	10	103.1
1991-2000	10	55.6
2001-10	10	29.5
2011-20	10	15.3
	Total	377.8

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 4

Period	Years	Millions of Barrels
1965-70	6	84.6
1971-80	10	228.5
1981-90	10	185.3
1991-2000	10	99.9
2001-10	10	53.0
2011-20	10	27.6
	Total	678.9

District 5

Period	Years	Millions of Barrels
1965-70	6	11.8
1971-80	10	31.8
1981-90	10	25.8
1991-2000	10	13.9
2001-10	10	7.4
2011-20	10	3.8
	Total	94.5

District 6

Period	Years	Millions of Barrels
1965-70	6	124.9
1971-80	10	337.4
1981-90	10	273.6
1991-2000	10	147.5
2001-10	10	78.2
2011-20	10	40.7
	Total	1,002.3

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 7B

Period	Years	Millions of Barrels
1965-70	6	118.9
1971-80	10	321.3
1981-90	10	260.4
1991-2000	10	140.5
2001-10	10	74.5
2011-20	10	38.7
		Total 954.3

District 7C

Period	Years	Millions of Barrels
1965-70	6	39.5
1971-80	10	106.7
1981-90	10	86.5
1991-2000	10	46.7
2001-10	10	24.8
2011-20	10	12.9
		Total 317.1

District 8

Period	Years	Millions of Barrels
1965-70	6	1,222.1
1971-80	10	3,301.9
1981-90	10	2,677.1
1991-2000	10	1,443.9
2001-10	10	765.7
2011-20	10	398.2
		Total 9,808.9

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 9

Period	Years	Millions of Barrels
1965-70	6	267.9
1971-80	10	723.9
1981-90	10	586.9
1991-2000	10	316.5
2001-10	10	167.9
2011-20	10	87.3
	Total	2,150.4

District 10

Period	Years	Millions of Barrels
1965-70	6	45.9
1971-80	10	124.0
1981-90	10	100.5
1991-2000	10	54.3
2001-10	10	28.7
2011-20	10	15.0
	Total	368.4

5. Estimation of Total Oil Production by Water Injection in Each Texas Railroad Commission District from 1965 to 2020 Inclusive.

District	Millions of Barrels
1	182.5
2	76.9
3	377.8
4	687.9
5	94.5
6	1,002.3
7B	954.3
7C	317.1
8	9,808.9
9	2,150.4
10	368.4
Total	16,012.0

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

6. Estimation of Total Water Required for the Production of Oil in Texas Railroad Commission Districts from 1965 to 2020 Inclusive.

District 1

Period	Years	Millions of Barrels
1965-70	6	265.6
1971-80	10	718.4
1981-90	10	582.7
1991-2000	10	314.7
2001-10	10	167.3
2011-20	10	86.6
	Total	2,135.3

District 2

Period	Years	Millions of Barrels
1965-70	6	50.9
1971-80	10	137.3
1981-90	10	111.3
1991-2000	10	59.9
2001-10	10	31.8
2011-20	10	16.4
	Total	407.6

District 3

Period	Years	Millions of Barrels
1965-70	6	447.4
1971-80	10	1,208.4
1981-90	10	979.5
1991-2000	10	528.2
2001-10	10	280.2
2011-20	10	145.3
	Total	3,589.0

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 4

Period	Years	Millions of Barrels
1965-70	6	1,379.0
1971-80	10	3,724.5
1981-90	10	3,020.4
1991-2000	10	1,628.4
2001-10	10	863.9
2011-20	10	449.9
	Total	11,066.1

District 5

Period	Years	Millions of Barrels
1965-70	6	96.8
1971-80	10	260.8
1981-90	10	211.6
1991-2000	10	114.0
2001-10	10	60.7
2011-20	10	31.2
	Total	775.1

District 6

Period	Years	Millions of Barrels
1965-70	6	349.7
1971-80	10	944.7
1981-90	10	766.1
1991-2000	10	413.0
2001-10	10	219.0
2011-20	10	114.0
	Total	2,806.5

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 7B

Period	Years	Millions of Barrels
1965-70	6	1,343.6
1971-80	10	3,630.7
1981-90	10	2,942.5
1991-2000	10	1,587.7
2001-10	10	841.8
2011-20	10	437.3
	Total	10,783.6

District 7C

Period	Years	Millions of Barrels
1965-70	6	462.1
1971-80	10	1,248.4
1981-90	10	1,012.0
1991-2000	10	546.4
2001-10	10	290.2
2011-20	10	150.9
	Total	3,710.0

District 8

Period	Years	Millions of Barrels
1965-70	6	8,921.3
1971-80	10	24,103.9
1981-90	10	19,542.8
1991-2000	10	10,540.5
2001-10	10	5,589.6
2011-20	10	2,906.9
	Total	71,605.0

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 9

Period	Years	Millions of Barrels
1965-70	6	2,893.3
1971-80	10	7,818.1
1981-90	10	6,338.5
1991-2000	10	3,418.2
2001-10	10	1,813.3
2011-20	10	942.8
	Total	23,224.2

District 10

Period	Years	Millions of Barrels
1965-70	6	587.5
1971-80	10	1,587.2
1981-90	10	1,286.4
1991-2000	10	695.0
2001-10	10	367.4
2011-20	10	192.0
	Total	4,715.5

7. Estimation of Total Water Required for the Production of Oil in Each Texas Railroad Commission District from 1965 to 2020 Inclusive.

District	Millions of Barrels
1	2,135.3
2	407.6
3	3,589.0
4	11,066.1
5	775.1
6	2,806.5
7B	10,783.6
7C	3,710.0
8	71,605.0
9	23,224.2
10	4,715.5
Total	134,817.9

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

8. Estimation of Total Water Required from Other Sources for the Production of Oil in Each Texas Railroad Commission District for Successive Time Periods from 1965 to 2020 Inclusive.

District 1

Period	Years	Millions of Barrels
1965-70	6	249.1
1971-80	10	574.7
1981-90	10	546.6
1991-2000	10	295.2
2001-10	10	156.9
2011-20	10	81.2
	Total	1,903.7

District 2

Period	Years	Millions of Barrels
1965-70	6	40.3
1971-80	10	108.6
1981-90	10	88.0
1991-2000	10	47.4
2001-10	10	25.2
2011-20	10	13.0
	Total	322.5

District 3

Period	Years	Millions of Barrels
1965-70	6	326.6
1971-80	10	882.1
1981-90	10	715.0
1991-2000	10	385.6
2001-10	10	204.5
2011-20	10	106.1
	Total	2,619.9

Table 5.-- Recapitulation of pertinent figures from Table 4--Continued

District 4

Period	Years	Millions of Barrels
1965-70	6	711.6
1971-80	10	1,921.8
1981-90	10	1,558.5
1991-2000	10	840.3
2001-10	10	445.8
2011-20	10	232.1
	Total	5,710.1

District 5

Period	Years	Millions of Barrels
1965-70	6	91.2
1971-80	10	245.7
1981-90	10	199.3
1991-2000	10	107.4
2001-10	10	57.2
2011-20	10	29.4
	Total	730.2

District 6

Period	Years	Millions of Barrels
1965-70	6	22.4
1971-80	10	60.5
1981-90	10	49.0
1991-2000	10	26.4
2001-10	10	14.0
2011-20	10	7.3
	Total	179.6

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 7B

Period	Years	Millions of Barrels
1965-70	6	1,252.2
1971-80	10	3,383.8
1981-90	10	2,742.4
1991-2000	10	1,479.7
2001-10	10	784.6
2011-20	10	407.6
	Total	10,050.3

District 7C

Period	Years	Millions of Barrels
1965-70	6	366.4
1971-80	10	990.0
1981-90	10	802.5
1991-2000	10	433.3
2001-10	10	230.1
2011-20	10	119.7
	Total	2,942.0

District 8

Period	Years	Millions of Barrels
1965-70	6	8,403.9
1971-80	10	22,705.9
1981-90	10	18,409.3
1991-2000	10	9,929.2
2001-10	10	5,265.4
2011-20	10	2,738.3
	Total	67,452.0

Table 5.--Recapitulation of pertinent figures from Table 4--Continued

District 9

Period	Years	Millions of Barrels
1965-70	6	2,604.0
1971-80	10	7,036.3
1981-90	10	5,704.6
1991-2000	10	3,076.4
2001-10	10	1,632.0
2011-20	10	848.5
	Total	20,901.8

District 10

Period	Years	Millions of Barrels
1965-70	6	584.0
1971-80	10	1,577.7
1981-90	10	1,278.7
1991-2000	10	690.8
2001-10	10	365.2
2011-20	10	190.8
	Total	4,687.2

9. Estimation of Total Water Required from Other Sources for the Production of Oil in Each Texas Railroad Commission District from 1965 to 2020 inclusive.

District	Millions of Barrels
1	1,903.7
2	322.5
3	2,619.9
4	5,710.1
5	730.2
6	179.6
7B	10,050.3
7C	2,942.0
8	67,452.0
9	20,901.8
10	4,687.2
Total	117,499.3

Table 6.--Preliminary estimation of water requirements for thermal recovery of oil in Railroad Commission Districts of Texas

(All figures in millions of barrels of 42 U.S. gallons.)

District	Number of fields	Estimated pore volume of reservoirs	Estimated oil content of reservoirs	Estimated water requirements for generation of steam	Estimated oil recovery
1	64	354.6	159.6	567.3	91.0
2	12	45.5	20.5	72.7	11.7
3	28	1,466.2	586.5	2,345.9	334.3
4	56	1,028.8	463.0	1,646.1	263.9
5	6	28.5	11.4	45.7	26.0
6	30	2,492.8	997.1	3,988.4	568.4
7B	1	.7	.3	1.2	.1
7C	3	346.8	138.7	555.0	79.1
8	7	751.0	300.4	1,201.7	171.2
9	10	22.7	9.1	36.4	5.2
10	0	.0	.0	.0	.0
Total	217	6,537.6	2,686.6	10,460.4	1,550.9

APPENDICES

APPENDIX A

Method of Calculation of Additional Water Injection Reserves from Future Oil Discoveries in Texas

Future discoveries of oil in the United States, from the Moore Chart F, calculated for succeeding time periods are estimated to be:

Period	Billions of Barrels
1965-70	16.0
1971-80	29.5
1981-90	20.5
1991-2000	17.0
2001-10	14.0
2011-20	11.5

It is estimated that 32.1 percent of reserves from future oil discoveries in the United States will be found in Texas.

It is estimated that the percentage of reserves from future oil discoveries in Texas which will be recovered by fluid injection will increase progressively in succeeding time periods according to the following schedule:

Period	Percent
1960	25.0
1965-70	30.0
1971-80	35.0
1981-90	40.0
1991-2000	45.0
2001-10	47.5
2011-20	50.0

Also that 85 percent of the fluid injection reserves will be recovered by water injection.

These various factors are employed in the following simple equations to determine additional water injection reserves in Texas from future discoveries.

Period	(a)		(b)		(c)		(d)		(e)
1965-70	16.0	x	0.321	x	0.300	x	0.85	=	1,310
1971-80	29.5	x	.321	x	.350	x	.85	=	2,817
1981-90	20.5	x	.321	x	.400	x	.85	=	2,374
1991-2000	17.0	x	.321	x	.450	x	.85	=	2,087
2001-10	14.0	x	.321	x	.475	x	.85	=	1,814
2011-20	11.5	x	.321	x	.500	x	.85	=	1,569
								Total	11,971
Texas Secondary Reserves by Water Injection as of January 1, 1965									4,060
									16,031

Where:

(a) = Estimated future discoveries of oil in the United States for succeeding time periods as determined by Moore's Chart F.

(b) = Estimated part of future discoveries in Texas.

(c) = Progressive increase in percentage of future discoveries in Texas in succeeding time periods to be produced by fluid injection.

(d) = Percentage of fluid injection reserves to be produced by water injection.

(e) = Millions of barrels.

APPENDIX B

Estimated Future Annual Production of Oil by Water Injection in Texas

Figures for annual production taken from special graph drawn for Texas and paralleling curve drawn for future secondary production in the United States by Albert E. Sweeney, Jr. All figures in millions of barrels of 42 U.S. gallons.

Year	Estimated Annual Production	Period	Estimated Production for Period
1965	275		
1966	298		
1967	321		
1968	344		
1969	367		
1970	390	1965-70	1,995
1971	422		
1972	454		
1973	486		
1974	518		
1975	550		
1976	564		
1977	578		
1978	592		
1979	606		
1980	620	1971-80	5,390
1981	586		
1982	552		
1983	518		
1984	484		
1985	450		
1986	422		
1987	366		
1988	344		
1989	338		
1990	310	1981-90	4,370
1991	296		
1992	282		
1993	268		
1994	251		
1995	240		
1996	228		
1997	216		
1998	204		
1999	192		
2000	180	1991-2000	2,347

(Continued on next page)

Year	Estimated Annual Production	Period	Estimated Production for Period
2001	170		
2002	160		
2003	150		
2004	140		
2005	130		
2006	120		
2007	110		
2008	100		
2009	90		
2010	80	2001-10	1,250
2011	77		
2012	74		
2013	71		
2014	68		
2015	65		
2016	63		
2017	61		
2018	59		
2019	57		
2020	55	2011-20	650
	Total 16,012		Total 16,012