REVIEW OF HYDROCARBON TRANSMISSION LINES CROSSING THE EDWARDS UNDERGROUND RESERVOIR

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FINAL REPORT

SwRI Project 22-4497

Prepared for

Edwards Underground Water District
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I. SUMMARY AND CONCLUSIONS

Although little information has been reported on contamination of groundwater from crude oil trunk pipelines, the significance of these pipelines cannot be minimized. Hydrocarbon transmission lines are of primary importance in the consideration of contamination potential. Four of these main trunk lines cross the Edwards Underground Reservoir (EUR) for a total length of 237 miles. These lines cross drainage basins which provide an estimated annual recharge of 20 percent to the total Edwards Aquifer. Limestone aquifers such as the Edwards afford little or no filtration capability to protect groundwater from hydrocarbon transmission line leaks or spills.

After surveying past experience associated with pipeline leaks, it was decided that the U.S. experience was an inadequate data base for predictive analysis; a review of Texas pipeline-related data provided a more adequate source of comparison. There have been nine reported leaks in the EUR from 1970 to the present (September 1976) with corrosion being the primary cause of such leaks. The total reported leaks in Texas from 1973 to 1975 were 1320; of these, 1008 were the result of crude oil pipeline corrosion. Pipelines crossing the EUR have experienced a significantly lower rate of leaks than pipelines over the rest of Texas. The EUR rate is less than 12 percent of the total Texas rate, and too few EUR leaks have occurred to indicate differences in causal factors of these failures. The 1975 Texas failure rate was determined to be 49.79 leaks/1000 miles/year while the EUR rate was determined to be 6.33 leaks/1000 miles/year. (A lognormal distribution provided the best model for the gross loss spill volume obtained from the total Texas data.)

Further study and assessment produced these additional conclusions concerning future hydrocarbon transmission line leaks:

(1) Using the pessimistic Texas rate assumption, there is a near certainty of at least one oil leak over the EUR each year. By using the EUR rate, there is a 77-percent chance of one or more leaks occurring in a year; thus, it is likely that one or more leaks will continue to occur over the EUR in most years.

(2) For both the U.S. and Texas crude oil pipeline leak experience, there is a trend of decreasing accidents in recent years.

(3) Using the Texas rate assumption, the largest leak over the EUR is likely (about a 61-percent probability) to be between 100 and 499 barrels for a 1-year period. Using the EUR rate, the largest spill is expected to be less than 100 barrels (69-percent probability) for the same time period.

(4) Using the Texas rate assumption, there is a high probability of the cumulative spill volume exceeding 1000 barrels for a time period of several years. The EUR rate indicates that the possibility of such a large spill volume is not too great for time periods of less than 10 years.

(5) Assuming that the EUR leak rate remains at its recent level (not considering the apparent trend in decreasing leak numbers), a sizable volume (2501 to 6500 barrels) of crude oil is likely to be spilled over the EUR over a 20-year period.

(6) The probability of a single leak greater than 10,000 barrels is negligible (0.1 percent) even for a 20-year time period using the EUR failure rate.

(7) The predicted impact of small leaks (0 to 100 barrels) in nonstream and intermittent stream areas on the aquifer would be minimal.

(8) The effect of a small leak entering a stream would likely be to cause oil to enter the aquifer.

(9) The predicted impact of a large leak in nonstream areas of the aquifer is minimal because of the physical distance from the streams.

(10) The predicted impact of a large leak on an intermittent or flowing stream on the aquifer is likely to be severe.

As of this date, the Texas Water Quality Board (TWQB) has not established specifications for the construction of new pipelines crossing the Edwards Aquifer recharge zone. The four companies presently operating the pipelines crossing the EUR function under Federal Department of Transportation rules and regulations applicable to interstate transmission lines. Furthermore, based on the data generated by this study, the need for pipeline retrofit modification on existing pipelines does not appear to be justified at this time.

II. RECOMMENDATIONS

The importance of protecting the Edwards Underground Reservoir from oil contamination should not be minimized. If a large volume of oil should enter the underground water system, the damage to the system would not be easily corrected. Even though pumping may remove some or all of the oil, this may not always be technically feasible. It is not known where, when, or how such oil might exit the aquifer and the ultimate consequences. The worst case might be the elimination of this water supply as a drinking water source to a large number of people for a sustained period of time. The most optimistic case may be that such oil would enter the aquifer and never interfere with drinking water supplies but exit through springs.

As described in this report, the probability of such a large leak occurring is low. A number of unknowns might even reduce this low probability even further. It is conceivable that future trends in the availability of crude oil might cause the discontinuation of these particular pipelines and also preclude the construction of additional pipelines over the EUR. Pipeline operators are interested and concerned with the protection of the environment and, as the cost of crude oil increases, the loss of this product is a strong economic incentive to prevent and/or reduce spills and leaks.

In view of these facts and uncertainties, the following recommendations are made:

(1) No construction modifications are recommended to existing pipelines. The possibility that construction modifications may change the present leak failure rate does exist. Based upon the existing data, the pipelines appear to be adequately protected.

(2) Work with the Texas Railroad Commission (TRC) to monitor the possibility of future crude oil pipeline construction. Extend the protection of the TWQB Edwards' Board Order to future pipelines, especially in the area of streams and stream crossings.

(3) Work with pipeline operators to ensure an awareness of spill-prevention techniques.

(4) TWQB adopt the DOT Part 195 regulations to control construction of intrastate pipelines within the Board's jurisdiction.

III. INTRODUCTION

The Edwards Underground Water District (EUWD) is responsible for the conservation, preservation, protection, and prevention of waste and pollution of the underground water known as the Edwards Underground Reservoir. The Edwards Underground Water District includes the artesian portion of the aquifer and recharge zone in Bexar, Comal, Hays, Medina, and Uvalde Counties. The drainage basins of rivers and streams serving as recharge to the aquifer are not included in the EUWD with the exception of those portions of the basins in the recharge area. A map of the region is presented in Figure 1.

Public concern for the protection of this high-quality water supply has resulted in recent enactment of local, state, and federal rules and regulations concerning protection of this vital resource for the region. EUWD has long recognized the importance of protection of the quality of this water and has maintained monitoring and surveillance programs of the recharge streams and the underground water. The present program is a logical extension of the desire of the EUWD to have knowledge of the potential contamination problems.

The objective of this present study was to quantify in some manner the contamination potential of hydrocarbon transmission lines crossing the EUR. The Texas Water Quality Board (TWQB) order 75-0128-20 (Edwards Board Order) recognizes that some potential for contamination exists through the inclusion in the order of the following section (VIII.A.4.g):

> Hydrocarbon transmission lines will be constructed in accordance with Board specifications in the absence of specifications of some other state or federal agency having jurisdiction to so regulate. Board specification will be based solely on the protection of the Edwards Underground Reservoir.

The Edward's Board Order does not address existing hydrocarbon transmission lines crossing the aquifer source zone (drainage basin of rivers crossing the recharge zone). Information concerning the potential for contamination of existing pipelines was not readily available to the EUWD in order to assist their decision-making processes. The information compiled in this report serves to fill that need.

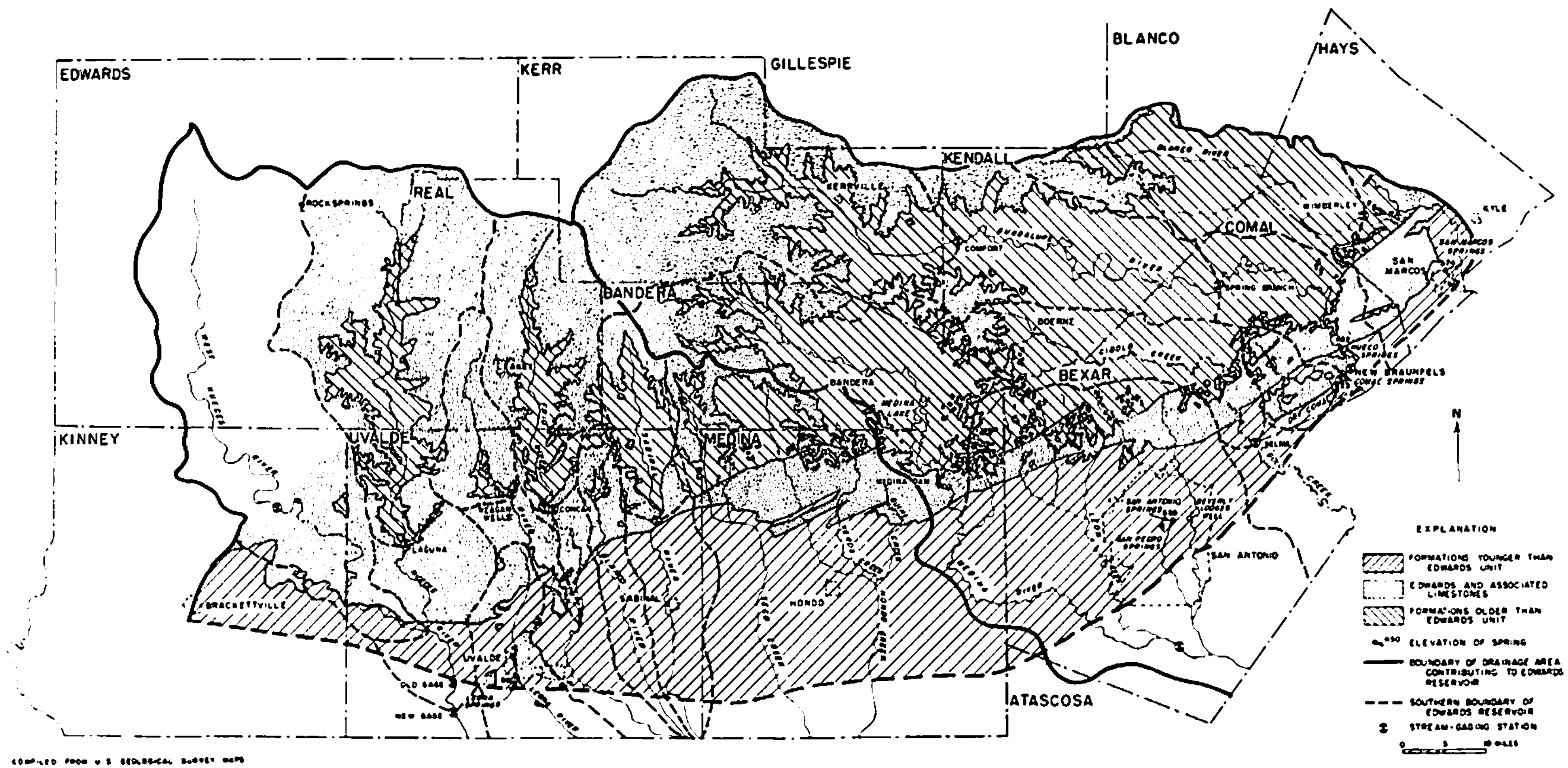

FIGURE 1. GEOLOGIC MAP SHOWING EXTENT OF EDWARDS RESERVOIR AND AREA CONTRIBUTING RECHARGE

IV. DESCRIPTION OF CURRENT SITUATION

Information concerning the pipelines was obtained from the Texas Railroad Commission, a commercial mapping service, and the pipeline companies. Crude oil main pipelines were examined exclusively. Even though gas pipelines do exist in the area, leaks and failures in such pipelines would not pose a serious threat to the underground water due to the nature of the material being transported. Maps of the four crude oil pipelines have been submitted under separate cover for use by EUWD staff.

A. General Description of Edwards Aquifer

The Edwards Underground Reservoir is the principal source of water for approximately one million people in the San Antonio area. This high quality water is used as a drinking water, industrial, and irrigation water source. The underground water also provides flow to springs and streams which provide a source of recreation and revenue to the area. The only treatment the water receives before use as drinking water is chlorination for disinfection purposes. With no alternative source of drinking water supply at the present, severe contamination of the groundwater would pose a serious economic and environmental problem for the area.[(1)*]

The recharge to the artesian portion of the aquifer is primarily from streams crossing the strip of faulted and porous limestone which extends the approximate length of the aquifer. The water enters the artesian aquifer at these locations. Some recharge is from precipitation which falls directly on the recharge zone. The recharge streams receive their flow from rainfall that falls within their basins. Some of this rainfall results in direct run-off and some feeds water-table aquifers within the area. The water-table aquifers supply base flow to many recharge streams.[(2)] The estimated recharge to the Edwards Aquifer for 37 years is presented in Table 1.[(3)]

Approximately 20 percent of the estimated recharge has exposure to pipelines. The Blanco River and adjacent land (6.2 percent) and the area between the Sabinal and Medina Rivers (14 percent) are the areas exposed to pipeline routes. This results in 80 percent of the estimated annual recharge not being exposed to contamination by pipeline leaks. These estimates of exposure were made based upon the fact that the pipelines' routes pass through the basins described above.

B. General Pipeline Information

Four companies have crude oil main lines crossing the drainage basin and recharge zone of the Edwards Aquifer. Table 2 presents the mileage distribution for these companies.

The Exxon and American Petrofina pipelines cross portions of Real, Kerr, Bandera, and Medina counties. The Texas-New Mexico pipeline crosses portions of Blanco and Hays counties with the Texas Pipeline Company line crossing Hays county.

The total volume contained within these pipelines is 130,000 barrels (5.5 million gallons). The annual average daily volume of crude oil carried by the four companies is 85,298 barrels (3.6 million gallons) per day.

*Superscript numbers in parentheses refer to the list of references at the end of this report.

TABLE 1. ESTIMATED RECHARGE TO THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, 1971

(In thousands of acre-feet, one acre-foot equals 325,851 gallons)

Basin	1971	1934-70 Average	% of Total Recharge
Nueces and West Nueces Rivers	263.4	96.5	18.5
Frio and Dry Frio Rivers	212.4	87.9	16.7
Sabinal River	39.2	32.2	6.2
Medina Lake	68.7	51.4	9.9
Cibolo and Dry Comal Creeks	82.4	90.7	17.4
Blanco River and adjacent areas	22.2	32.5	6.2
Area between Sabinal and Medina Rivers	150.3	73.1	14.0
Area between Cibolo Creek and Medina River	81.4	57.0	10.9
TOTALS	920.0	521.2	

TABLE 2. CRUDE OIL PIPELINES CROSSING THE EDWARDS UNDERGROUND RESERVOIR

Company	Pipeline Diameter (inches)	Length of Pipeline (miles)	Total Company Pipeline Length (miles)
Exxon	12	23.9	
	10	79.2	103.1
American Petrofina	10	67.4	67.4
Texas-New Mexico	12	45.3	45.3
Texas	6	21.0	21.0
Total miles over Edwards Underground Reservoir			236.8

The type of construction of each pipeline varies with the age of the particular line. The Exxon lines vary from 29 to 49 years old, with the older lines being screw-coupled, greased, and buried. Approximately 60 to 70 percent of the screw-couplings are not welded. The newer lines are all welded, coated, wrapped, and buried. The American Petrofina line is 26 years old and is welded, coated, wrapped, and buried. The Texas-New Mexico line is 47 years old and is of welded steel bell and spigot construction. The Texas Pipeline Company line is 28 years old and constructed of welded seamless pipe which has been coated and wrapped. The pipelines are pressure tested and operated at some value below the test value.

V. CONTAMINATION POTENTIAL

A. Pipeline System Description

Oil spills on land come from a variety of sources, the most common of which are tank farms, pipelines, and transport tanks.[4] Crude oil pipelines are the source of concern for the present study. A crude oil pipeline consists of the following components:[5]

(1) Interconnecting pipeline with associated valves
(2) Originating station
(3) Booster stations
(4) Injection stations
(5) Terminal.

For the pipelines in the Edwards Area, the interconnecting pipeline and booster stations are of primary interest. Not considering catastrophic accidents such as earthquakes, explosions, or major fires, most oil spills which result in potential environmental impact can be categorized as due to equipment failure and/or human error.[5]

Examples of equipment failure include external and internal corrosion, valve and pump failure, and pipe rupture. In terms of equipment failure, corrosion is the source of greatest concern because other types of equipment failure can result from corrosion. Internal corrosion is not a problem in most crude oil pipelines. Main trunk pipelines are rarely subject to severe internal corrosion even when transporting sour crude oil. Sour crudes contain hydrogen sulfide. The turbulent flow prevents the corrosive agents from remaining in contact with internal surfaces.[6]

External corrosion is a natural process that has always created problems in use of pipelines. External corrosion can be caused by dissimilar metals, soil conditions, surface conditions of metals, and stray current. The primary methods of corrosion control are protective coatings and cathodic protection. Pipeline companies generally recognize that effective control of pipeline corrosion is essential for economic success and maintenance of public confidence in their systems.[6]

Human error resulting in leaks or spills includes such activities as:[5]

(1) Valve operation (i.e., leaving valves open or closed).
(2) Heavy equipment operation in vicinity of pipelines.
(3) Vandalism.

Potentially the most serious cause of leaks in terms of volume loss is activity involving construction operations in the area of buried pipelines. Such leaks are caused by penetration of the pipeline by heavy equipment when digging is taking place over the pipeline.

B. Contamination of Underground Water

A literature review produced little information concerning actual contamination of underground water by crude oil trunk pipelines. A series of five computer data bases,

(1) Enviroline
(2) Compendix
(3) Chemcon
(4) Smithsonian Science Information Exchange
(5) Georeference

produced essentially no reference to contamination of underground water supplies because of crude oil pipelines.

A review of the Texas Water Development Board Water Resource Reports[7] did produce examples of groundwater contamination from petroleum products. Primarily, these contamination reports were the result of leaks from gasoline storage tanks contaminating groundwater. Two such reports were in the Leon Valley region northwest of San Antonio. Apparently gasoline storage tanks leaked over a period of time. Water was pumped from the wells to remove the gasoline.[8-9] Similar cases of gasoline contamination were reported in other areas of the state. Prolonged pumping of the water apparently removed most of the contamination.[10]

A residential community in the upper Midwest reported contamination of a shallow water-table aquifer involving 500,000 gallons of hydrocarbon product. The product, reported to be 80 percent gasoline, had accumulated over a long period of time. The report did not indicate the source of the hydrocarbon product. The incident is useful in describing the recovery operation. A large well was drilled and dual pumps installed to remove the material. One pump was placed below the product-water interface and the other pump was placed within the product level. The water pump removed water to draw down the water level to allow the product to flow into the well on top of the water. The pump in the product level removed the contaminating material.[11]

A method used to prevent groundwater contamination from a refinery in Switzerland consisted of placement of an impermeable wall around the potential contamination area. The wall surrounding the buildings was constructed of concrete with bentonite added. The area was underlain with a low-permeability layer which served to retain the groundwater. Drains were placed in this "reservoir" to remove the contaminated water.[12]

In pipelines connecting Rotterdam, Netherlands, and Antwerp, Belgium, special measures were being designed into the multiple pipeline routes. These proposed designs include concentric pipes, cathodically protected externally and with sand in the annular space inside and pipelines laid over a bed of sand over a PVC sheet draped in a shallow trench to form a trough. The estimated cost of such protective features was reported to be considerable.[13]

In the Final Environment Impact Statement-Proposed Trans-Alaska Pipeline, no specific mention was made of the potential for oil contamination of underground water supplies. The primary emphasis was on the prevention of underground water supplies. The primary emphasis was on the prevention of surface contamination by design techniques such as detection of leaks and special construction.[14]

The natural protection afforded by limestone aquifers was addressed in a report on such an aquifer in upland Great Britain. The report indicated that the underground movement of water within massive, fissured, or cavernous limestones was largely confined to conduits which afford no natural filtration to the groundwater. The report concluded that any pollutant introduced into the limestone, especially below the level of the soil, was likely to reappear at a spring within a matter of time with relatively little dilution.[15]

VI. ANALYSIS OF FREQUENCY OF PIPELINE LEAKS

A. United States Experience

The leak history statistics of pipelines in the United States were obtained from the Alyeska Pipeline Service Company (1971) "Project Description of the Trans-Alaska Pipeline System" (APSC). The Department of Transportation requires a reporting of leaks of more than 50 barrels on interstate pipelines. The records indicate for the years 1968, 1969, and 1970, the total number of reported leaks for more than 230,000 miles of line were 499, 403, and 347, respectively. Approximately 50 percent of these reported leaks were due to external corrosion. APSC did not attempt to predict or model spills that might occur as a result of operation of the Trans-Alaska pipeline. The reason given was that the data base was inadequate for this type of prediction and that improvements in the pipeline technology made such predictions inaccurate. Because the U.S. data were based only on interstate pipelines and on spills greater than 50 barrels, it was felt that the present study should be based upon the Texas experience.

B. Texas Experience

1. Data Sources

The Texas Railroad Commission requires that the operators of hydrocarbon pipelines promptly report all spills with a gross loss equaling or exceeding 5 barrels that occur in Texas to the Railroad Commission on a standard form. Spills of less than 5 barrels are frequently reported also. Beginning with the 1973 calendar year, the Railroad Commission has compiled these spill reports on an automated data base. Southwest Research Institute has obtained computer printouts of all these spill reports by year and by facility involved for 1973, 1974, and 1975. The Railroad Commission files for 1970, 1971, and 1972 were also searched for reports of spills over the EUR. The computer printouts and the manual search of the Railroad Commission reports constitute the primary source of data for this analysis.

For each reported hydrocarbon spill, the Texas Railroad Commission printout, "Losses of Spills by Transporter," identified the pipeline operator (company), county, location, type of liquid, date of loss, gross loss, recovery, net loss, facility involved, cause of loss, remedial measures, and remarks. The hydrocarbon volumes reported as the gross loss and the net loss were, of necessity, estimates. The method by which the operator estimated the gross loss and the net loss was not specified; hence, the accuracy of the gross loss and net loss estimates is unknown.

Southwest Research Institute also obtained detailed maps of all the counties containing any part of the EUR. These maps identified all the existing hydrocarbon pipelines. The maps were used both to calculate the number of trunk pipeline miles over the reservoir and to determine whether the spills occurring in these counties were actually over the reservoir.

2. Pipeline and Spill Summary

Information detailing the numbers, length, and volume of pipelines crossing the EUR was presented in Table 2. The pipeline-related spills over the EUR are presented in Table 3 as they were

TABLE 3. REPORTED PIPELINE-RELATED SPILLS OVER THE EDWARDS UNDERGROUND RESERVOIR FROM 1970 THROUGH 1975*

Date of Spill	County	Pipeline Company	Gross Loss, Bbls	Net Loss, Bbls	Facility Involved	Cause of Loss
6/24/70	Hays	Texas N.M.	3	3	Pipeline	Other
12/2/70	Hays	Texas N.M.	0	0	Pipeline	Corrosion-Rust
12/23/70	Hays	Texas N.M.	1	1	Pipeline	Corrosion-Rust
12/26/70	Hays	Texas N.M.	3	3	Pipeline	Corrosion-Rust
4/19/71	Bandera	ARCO(Amer. Petro.)	10	10	Pipeline	Corrosion-Rust
5/18/71	Comal	Texas	2	2	Pipeline	Corrosion-Rust
11/13/72	Hays	Texas N.M.	4	4	Valve	Corrosion-Rust
7/23/74	Medina	Amer. Petrofina	200	40	Pipeline	Corrosion-Rust
6/23/75	Blanco	Texas N.M.	29	4	Pipeline	Corrosion-Rust

Note: Since all of the hydrocarbon pipelines over the Edwards Underground Reservoir transport crude oil, all of the reported spills are crude oil spills.

*Reported to the Texas Railroad Commission.

reported to the TRC. As of September 1976, no spills have been reported to the TRC for the calendar year 1976. The information presented in this table includes the dates of the spill, location, operator, loss volume, and apparent cause of loss. An annual summary of reported leaks in Texas and over the EUR is presented in Table 4. As can be seen from this data, the number of incidents and net volume lost appears to be decreasing for the total Texas experience from 1973 to 1975.

TABLE 4. ANNUAL SUMMARY OF REPORTED PIPELINE-RELATED SPILLS IN TEXAS AND OVER THE EDWARDS UNDERGROUND RESERVOIR

Year	Reported Pipeline-related Spills*					
	State of Texas			Edwards Underground Reservoir		
	Number of Spills	Gross Loss, Bbls.	Net Loss, Bbls.	Number of Spills	Gross Loss, Bbls.	Net Loss, Bbls.
1970				4	7	7
1971				2	12	12
1972				1	4	4
1973	1520	263,932	148,855	0	0	0
1974	1564	239,914	124,569	1	200	40
1975	1320	190,938	107,006	1	29	4

*Reported to the Texas Railroad Commission.

The total Texas distribution of reported hydrocarbon losses from the pipeline-related spills in 1975 is presented in Table 5. The data indicate that the crude oil trunk line corrosion-rust represents the largest portion of hydrocarbon spills. The total number of incidents was 1320, with 1008 being the result of crude oil pipeline corrosion.

Numerous combinations of the liquid types, facility, cause of loss, and loss type (gross or net) of the Texas hydrocarbon spills are presented in Table 5. This data set has been subjected to a complete statistical and probabilistic analysis. The analyses are based on the gross losses in the 1320 pipeline-related spills of all liquid types, in all facilities, and due to all causes that were reported in Texas in 1975. The excessive quantity of the spill data base precluded parallel analyses of the subsets. However, some of the analyses were also performed on an important subset: the gross and net losses from the 1008 reported crude oil pipeline failures caused by corrosion and rust in Texas in 1975. Since these analyses yielded very similar results, only the results for the total 1975 data set are herein reported.

C. Probability Models

There are three major objectives of this statistical analysis of Texas hydrocarbon pipeline spill data:

(1) Characterize and determine the frequency of structural failures of hydrocarbon transmission lines in Texas and over the Edwards Underground Reservoir.

(2) Predict the probability of occurrence and the probable maximum size of future hydrocarbon spills over the Edwards Underground Reservoir.

(3) Predict the total volume of hydrocarbons likely to be spilled over the Edwards Underground Reservoir in all the pipeline failures anticipated in the next 20 years.

Probability models were developed for the distribution of the number of pipeline-related spills per thousand miles of pipeline per year and for the distribution of the loss volume per spill. These probability distribution models are utilized in probability decomposition formulas to calculate the probabilities required to achieve the second and third analysis objectives previously listed. This section specifies the assumptions, notation, and distributional models, and derives the probability calculation formulas used in the ensuing analysis.

1. Assumptions

(a) There is an equal probability of a failure (spill) per unit pipeline length and per unit time throughout Texas. This means that a failure is just as likely to occur on any mile of pipeline (over the Edwards Underground Reservoir) as on any other mile of pipeline in Texas; i.e., all of Texas has the same basic failure rate per pipeline mile. Also, for a given mile of pipeline, the failure rate is the same from year to year. In statistical terminology, the Texas pipeline-related failures represent a Poisson process.

TABLE 5. DISTRIBUTION OF REPORTED HYDROCARBON LOSSES FROM PIPELINE-RELATED SPILLS IN TEXAS IN 1975 BY LIQUID TYPE, FACILITY, AND CAUSE OF LOSS

Type of Liquid	Facility Involved	Cause of Loss								
		All Causes of Loss			Corrosion-Rust			Other Causes*		
		Number of Spills	Gross Loss, Bbls.	Net Loss, Bbls.	Number of Spills	Gross Loss, Bbls.	Net Loss, Bbls.	Number of Spills	Gross Loss, Bbls.	Net Loss, Bbls.
All Liquids	All Facilities	1320	190,938	107,006	1039	130,257	77,773	281	60,681	29,233
	Pipeline	1190	166,557	98,463	1025	129,578	77,515	165	36,979	20,948
	Valve	79	10,764	2,581	14	679	258	65	10,085	2,323
	Pump Station/Terminal	6	144	80	0	0	0	6	144	80
	Other**	45	13,473	5,882	0	0	0	45	13,473	5,882
Crude Oil	All Facilities	1288	157,838	77,332	1022	110,666	58,182	266	47,172	19,150
	Pipeline	1162	133,595	68,902	1008	109,987	57,924	154	23,608	10,978
	Valve	77	10,679	2,496	14	679	258	63	10,000	2,238
	Pump Station/Terminal	6	144	80	0	0	0	6	144	80
	Other**	43	13,420	5,854	0	0	0	43	13,420	5,854
Products	All Facilities	27	32,800	29,374	16	19,581	19,581	11	13,219	9,793
	Pipeline	25	32,722	29,321	16	19,581	19,581	9	13,141	9,740
	Valve	1	35	35	0	0	0	1	35	35
	Other**	1	43	18	0	0	0	1	43	18
Gas Well Liquid	All Facilities	5	300	300	1	10	10	4	290	290
	Pipeline	3	240	240	1	10	10	2	230	230
	Valve	1	50	50	0	0	0	1	50	50
	Other**	1	10	10	0	0	0	1	10	10

* Other causes include equipment failure, construction, company or other human error, act of God, vandalism, and miscellaneous others.

** Other facilities involved include pumps, nipples, connectors, etc.

(b) The loss volume from each pipeline-related hydrocarbon spill in Texas is independent and identically distributed. Thus, the loss volumes from all spills in Texas can be considered as various observations from a single statistical distribution model.

(c) From assumptions a and b, it follows that the recent Texas pipeline-related failure rate and spill loss sizes are representative of what can be anticipated for the Edwards Underground Reservoir pipelines in the future.

2. Notation

The notations for the major random variables, their values, and their interpretation are presented below:

Random Variable	Value	Interpretation
K	k	Number of pipeline failures (hydrocarbon spills)
V	v	Volume of hydrocarbons spilled in a single pipeline failure
Z	z	Amount (volume) of hydrocarbons spilled over a specified length of time and miles of pipeline

The notation $P(X \leqslant x)$ is read as "the probability that random variable X is less than or equal to x." Other symbols will be explained as they are introduced.

3. Probability Distribution Models

From assumption a, it follows that K has a Poisson distribution. We will denote its parameter as λt where

λ – number of pipeline failures per thousand pipeline mile years
t – number of thousands of pipeline mile years

The Poisson probability function for K is given by

$$P(K = k) = e^{-\lambda t} \frac{(\lambda t)^k}{k!} \tag{1}$$

where $k! = (k)(k-1)(k-2) \cdots (3)(2)(1)$ and $e = 2.71828$. Thus, for example, the probability that there will be $k = 0$ failures in t thousand mile-years is

$$P(K = 0) = e^{-\lambda t} \frac{(\lambda t)^0}{0!} = e^{-\lambda t}$$

The probability of exactly $k = 4$ failures is

$$P(K = 4) = e^{-\lambda t} \frac{(\lambda t)^4}{4!} = e^{-\lambda t} \frac{\lambda^4 t^4}{24}$$

The assumptions do not specify the distributional model for V. The range and distribution of values of V suggest the negative exponential distribution and the lognormal distribution as potential models. The lognormal distribution function for V with parameters μ_L and σ_L is denoted as P_{LN} and

$$P_{LN}\ (V \leqslant v) = N\left(\frac{\log v - \mu_L}{\sigma_L}\right) \tag{2}$$

where N is the tabulated standard normal distribution function. The negative exponential distribution function for V with parameter θ is denoted as P_{NE} and defined as

$$P_{NE}\ (V \leqslant v) = 1 - e^{-v/\theta} \tag{3}$$

4. Probability Calculation Formulas

Z is the total volume of hydrocarbons spilled in all the pipeline failures occurring over t thousand pipeline mile-years. $Z = V_1 + V_2 + \cdots + V_K$ for the K spills in this interval. The distribution function $P(Z \leqslant z)$ can be computed by decomposing $P(Z \leqslant z)$ over all possible number of spills K:

$$\begin{aligned} P(Z \leqslant z) &= P\left(\sum_{i=1}^{K} V_i \leqslant z\right) \\ &= P(K = 0) + P(Z = V \leqslant z \mid K = 1)\, P(K = 1) \\ &\quad + P(Z = V_1 + V_2 \leqslant z \mid K = 2)\, P(K = 2) \\ &\quad + P(Z = V_1 + V_2 + V_3 \leqslant z \mid K = 3)\ P(K = 3) \\ &\quad + \ldots . \end{aligned} \tag{4}$$

provided the terms in this series approach 0 rapidly enough.

In Section D, we will find that for the gross loss volumes of the spills occurring in Texas in 1975, the lognormal distribution model $P_{LN}\ (V \leqslant v)$ is much superior to the negative exponential distribution model $P_{NE}\ (V \leqslant v)$ in describing the distribution of spill volumes. Thus, we can approximate the Equation (4) term for a single spill

$$P(V \leqslant z \mid K = 1) \simeq P_{LN}\ (V \leqslant z) = N\left(\frac{\log z - \mu_L}{\sigma_L}\right)$$

from Equation (2).

However, with a lognormal model for each V, the calculation of $P(V_1 + V_2 \leqslant z \mid K=2)$, $P(V_1 + V_2 + V_3 \leqslant z \mid K = 3)$, and higher order terms is mathematically intractable. Numerical approximation by computer is possible, but beyond the project scope and unwarranted because of the imprecision of the estimated loss data. Because $P(V_1 + V_2 \leqslant z \mid K = 2), P(V_1 + V_2 + V_3 \leqslant z \mid K = 3)$, and the higher order terms can be mathematically expressed in closed form when each V is assumed to have a negative exponential distribution, this negative exponential model assumption has been made for V. By induction, beginning with $k = 1$, we derived the following formula for the distribution of the total volume of k spills when each spill volume V has a negative exponential distribution with parameter θ:

$$P_{NE}(V_1 + V_2 + \cdots + V_k \leqslant z) = P_{NE}\left(\sum_{j=1}^{k} V_j \leqslant z\right) \tag{5}$$

$$= 1 - \left[e^{-z/\theta}\right]\left[\sum_{j=1}^{k} \frac{1}{(j-1)!}\left(\frac{z}{\theta}\right)^{(j-1)}\right]$$

By utilizing the lognormal model for V when $K = 1$ [Equation (2)], the negative exponential model for each V_i when $K > 1$ [Equation (5)], and the Poisson model for K [Equation (1)], we obtain the following decomposition calculation formula for the total volume spilled Z from Equation (4):

$$P(Z \leqslant z) = e^{-\lambda t} + \lambda t\, e^{-\lambda t} N\left(\frac{\log z - \mu_L}{\sigma_L}\right) + \sum_{k=2}^{\infty}\left\{(e^{-\lambda t})\frac{(\lambda t)^k}{k!}\right\}\left\{1 - \left[e^{-z/\theta}\right]\left[\sum_{j=1}^{k}\frac{1}{(j-1)!}\left(\frac{z}{\theta}\right)^{(j-1)}\right]\right\} \tag{6}$$

A computer program was written to calculate $P(Z \leqslant z)$ for various values of λ and t using Equation (6). The order of calculation was carefully determined to avoid round-off error problems. In practice, the summation $\sum_{k=2}^{\infty}$ was only performed over enough terms so that the sum of the remainder of the terms is inconsequential. The estimated values of the parameters μ_L, σ_L, and θ are obtained in Section E.

Use of the negative exponential model for $k \geqslant 2$ does introduce inaccuracy into the calculation of $P(Z \leqslant z)$ via Equation (6). However, the only terms for which sizable errors may occur are the low k terms ($k = 2$, $k = 3$, etc.). For larger k values, the central limit theorem, the law of large numbers[16], and the fact that Equation (5) is exact ensure that $P_{NE}(\sum_{j=1}^{k} V_j \leqslant z)$ approaches the proper value because $1/n \sum_{j=1}^{k} V_j$ becomes a normal random variate and approaches the expected value of V. Depending on the value of y, most of the probability $P(K = k)$ often occurs for $k = 0$ and $k = 1$ or for high k values ($k > 10$). In these cases, Equation (6) should yield a satisfactory estimate of $P(Z \leqslant z)$.

To satisfy objective 2 regarding probable maximum spill size, it is necessary to calculate $P(V_{max} \leqslant v)$, the probability that the largest spill V_{max} in period t is less than a specified volume v. Again, we decompose the probability over all possible number of spills K:

$$P(V_{max} \leqslant v) = P(K = 0) + P(K = 1)\,P(V_{max} \leqslant v \mid K = 1) + P(K = 2)\,P(V_{max} \leqslant v \mid K = 2) + \ldots \tag{7}$$

Now V is approximately lognormally distributed with parameters μ_L and δ_L. In addition, the distribution of the maximum of k values is the kth power of the distribution function[17]

$$P(V_{max} \leqslant v \mid K = k) = \Big[P(V \leqslant v)\Big]^k = \left[N\left(\frac{\log v - \mu_L}{\sigma_L}\right)\right]^k \tag{8}$$

Inserting Equations (1) and (8) into Equation (7) for each value of K yields

$$P(V_{max} \leqslant v) = e^{-\lambda t} + \sum_{k=1}^{\infty} \left[(e^{-\lambda t})\frac{(\lambda t)^k}{k!}\right]\left[N\left(\frac{\log v - \mu_L}{\sigma_L}\right)\right]^k \tag{9}$$

A computer program was also written to compute $P(V_{max} \leqslant v)$ using Equation (9). Again the number of calculated terms was based on the size and decay rate of successive terms.

D. Parameter Estimation and Selection of the Spill Volume Distribution Model

A frequency distribution of the volumes of the reported hydrocarbon gross losses from pipeline-related spills in Texas in 1975 is presented in Table 6. A histogram of this frequency distribution is shown in Figure 2. The spill volume distribution is extremely skewed to the right. The most frequently reported spill volumes were between 5 and 19 barrels. Of the spills, 64 percent were less than 50 barrels. However, there were some extremely large spills also: 37 between 500 and 999 barrels; 24 between 1000 and 4999 barrels; and 5 over 5000 barrels.

Using the 1975 Texas sample of n = 1320 gross loss volumes, the usual unbiased estimates of the lognormal parameters μ_L and σ_L and of the negative exponential parameter θ were calculated. The lognormal parameter estimates using common logarithms are

$$\hat{\mu}_L = \frac{1}{n}\sum_{i=1}^{n} \log v_i = 1.5669$$

$$\hat{\sigma}_L = \frac{1}{n-1}\sum_{i=1}^{n} (\log v_i - \mu_l)^2 = 0.6240$$

This yields a geometric mean spill volume of 36.89 barrels. The negative exponential parameter estimate

$$\hat{\theta} = \frac{1}{n}\sum_{i=1}^{n} v_i = 144.65$$

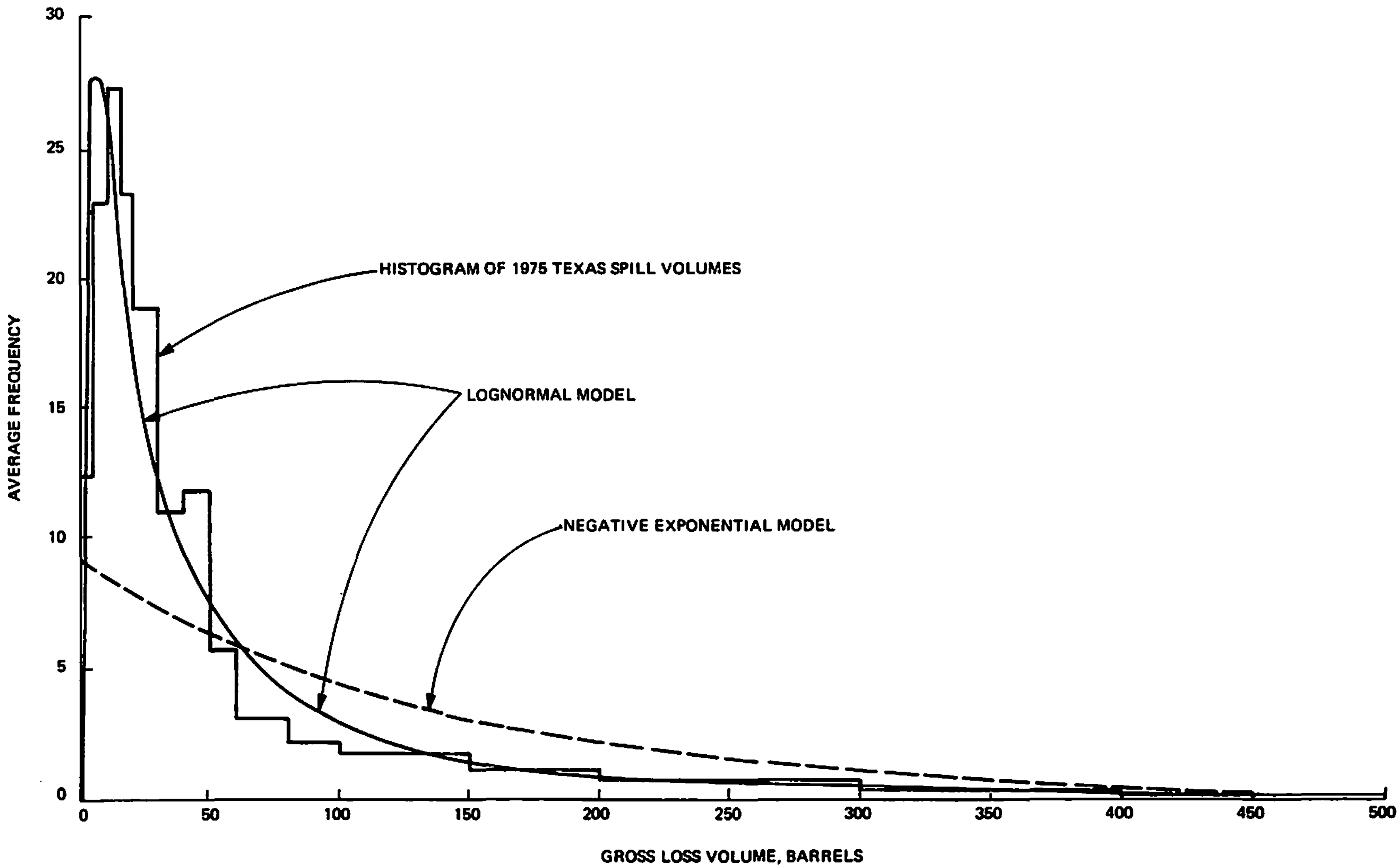

FIGURE 2. FITTING THE VOLUME DISTRIBUTION HISTOGRAM OF REPORTED HYDROCARBON GROSS LOSSES FROM PIPELINE-RELATED SPILLS IN TEXAS IN 1975 TO LOGNORMAL AND NEGATIVE EXPONENTIAL VOLUME DISTRIBUTIONS

TABLE 6. VOLUME DISTRIBUTION OF THE REPORTED HYDROCARBON GROSS LOSSES FROM PIPELINE-RELATED SPILLS IN TEXAS IN 1975

Gross Loss Interval, Bbls.	Frequency of Spills	Cumulative Frequency	Sample Cumulative Distribution Function
0 - 4	61	61	.0462
5 - 9	114	175	.1326
10 - 14	137	312	.2364
15 - 19	116	428	.3242
20 - 29	188	616	.4667
30 - 39	110	726	.5500
40 - 49	116	842	.6379
50 - 59	57	899	.6811
60 - 79	61	960	.7273
80 - 99	42	1002	.7591
100 - 149	94	1096	.8303
150 - 199	54	1150	.8712
200 - 299	56	1206	.9136
300 - 399	27	1233	.9341
400 - 499	21	1254	.9500
500 - 999	37	1291	.9780
1000 - 4999	24	1315	.9962
5000 +	5	1320	1.0000

is the arithmetic mean spill volume (144.65 barrels). The discrepancy between the geometric and arithmetic mean spill volume estimates is indicative of the extreme skewness of the spill volume distribution.

The distribution functions for the negative exponential and lognormal models using the preceding parameter estimates were evaluated at each of the histogram interval boundaries. A comparison of these model distribution functions with the 1975 Texas sample distribution function is shown in Table 7. The corresponding density functions are plotted versus the same histogram in Figure 2. This figure displays the evident superiority of the lognormal model over the negative exponential model in describing the gross loss spill volume distribution.

To confirm our graphic impression of the lognormal model's superiority, two Kolmogorov-Smirnov distribution goodness-of-fit tests[17] were conducted. The null hypotheses that the 1975 Texas sample of 1320 spills is a random sample from the distributional model was tested for both the negative exponential model and the lognormal model. The maximum deviations at the 17 boundary points shown in Table 7 were $D = 0.3481$ at 49.5 barrels for the negative exponential model, and $D = 0.0569$ at 49.5 barrels for the lognormal model. The rejection levels are $D\ (.05) = 0.0374$ at the 5-percent

TABLE 7. COMPARISON OF THE NEGATIVE EXPONENTIAL AND LOGNORMAL MODELS FOR FITTING THE 1975 TEXAS SAMPLE OF GROSS SPILL LOSSES: BASED ON CUMULATIVE DISTRIBUTION FUNCTIONS

Gross Loss Interval Upper Limit, Bbls.	Gross Loss Cumulative Distribution Functions		
	1975 Texas Sample (1320 Spills)	Negative Exponential Model	Lognormal Model
4.5	.0462	.0306	.0716
9.5	.1326	.0636	.1726
14.5	.2364	.0953	.2578
19.5	.3242	.1261	.3323
29.5	.4667	.1844	.4384
39.5	.5500	.2390	.5185
49.5	.6379	.2898	.5810
59.5	.6811	.3372	.6340
79.5	.7273	.4227	.7035
99.5	.7591	.4974	.7551
149.5	.8303	.6442	.8350
199.5	.8712	.7482	.8798
299.5	.9136	.8739	.9274
399.5	.9341	.9368	.9513
499.5	.9500	.9684	.9651
999.5	.9780	.9990	.9892
4999.5	.9962	1.0000	.9997
--	1.0000	1.0000	1.0000

level, and D (.01) = 0.0449 at the 1-percent level. The test is not exact because only 17 of the several hundred distinct volume boundaries were compared, and because the level of the test is not adjusted for the two lognormal and one negative exponential parameter estimates. Nevertheless, the Kolmogorov-Smirnov (K-S) test clearly demonstrates the superiority of the lognormal spill volume model. The negative exponential model is grossly inadequate. The K-S test also rejects the lognormal model, but since the sample size of 1320 is so large, hardly any null hypotheses would be accepted. The lognormal model is obviously the best gross loss spill volume distribution available.

E. Comparison of the Pipeline Failure Rates of Texas and the Edwards Underground Reservoir

As previously stated, our first assumption states that the rate of pipeline failures resulting in hydrocarbon spills per unit pipeline length and per unit time is the same throughout Texas. This assumption has been made because the number of recent pipeline failures over the EUR is insufficient to obtain an accurate failure rate estimate for projecting future spills over the reservoir. However, by considering longer time intervals, 1970 through 1975 for the EUR, and 1973 through 1975 for the entire State of Texas, it is possible to test the validity of the assumption by comparing the reservoir with the rest of Texas.

Let λ_{EUR} denote the pipeline failure rate over the EUR, and let λ_{TX} denote the failure rate for the remainder of Texas. The units for λ are spills per thousand pipeline miles per year. Our null hypothesis is that the EUR and Texas failure rates are the same ($\lambda_{EUR} = \lambda_{TX}$). This null hypothesis is tested against the alternative that the reservoir failure rate is less than the Texas rate ($\lambda_{EUR} < \lambda_{TX}$). We still assume that the failure rates λ_{EUR} and λ_{TX} have Poisson distributions. Under the null hypothesis, the test statistic

$$T = \frac{\lambda_{TX} - \lambda_{EUR}}{\sqrt{\lambda_{TX} + \lambda_{EUR}}}$$

with a continuity correction is approximately a standard normal deviate.[18] The failure rates can be estimated from the Table 4 data and from the facts that there are 236.8 miles of crude oil trunkline over the reservoir, and 26,513 − 236.8 = 26,276 miles of crude oil trunklines in the rest of Texas. The 1970 to 1975 Edwards Underground Reservoir failure rate was

$$\hat{\lambda}_{EUR} = \frac{(4 + 2 + 1 + 0 + 1 + 1) \text{ spills/6 years}}{0.2368 \text{ thousand pipeline miles}} = 6.334 \text{ spills/thousand mile-years}$$

The 1973 to 1975 failure rate for the rest of Texas was

$$\hat{\lambda}_{TX} = \frac{(1520 + 1563 + 1319) \text{ spills/3 years}}{26.276 \text{ thousand pipeline miles}} = 55.843 \text{ spills/thousand mile-years}$$

The continuity corrections are $\frac{0.5 \text{ spills/6 years}}{0.2368 \text{ thousand miles}} = 0.352$ spills/thousand mile-years for the reservoir and $\frac{0.5 \text{ spills/3 years}}{26.276 \text{ thousand miles}} = 0.006$ spills/thousand mile-years for the remainder of Texas. Thus the test statistic is

$$T = \frac{(55.843 - 0.006) - (6.334 + 0.352)}{\sqrt{55.843 + 6.334}} = 6.23$$

The 1-percent significance level for T is 2.33 and the 0.1-percent level is 3.09. Thus, the null hypothesis must definitely be rejected. The pipelines over the Edwards Underground Reservoir have experienced a significantly lower rate of reported hydrocarbon spills than have the pipelines over the rest of Texas.

Since the rate of oil spills over the EUR has been less than the 12-percent rate in the remainder of Texas, it is natural to investigate the reason for this discrepancy. Possible reasons include the effects of soil acidity on rate of pipeline corrosion, special precautions in pipeline construction and/or maintenance, fewer accidental pipeline ruptures due to less construction activity, irregularities in spill reporting, and/or data processing anomalies. Table 5 does indicate the relative frequency of the various causes of loss. Corrosion/rust caused 79 percent of all the spills in Texas in 1975, and 86 percent of the pipeline spills. However, the spills due to other causes tended to be larger. There have been insufficient EUR spills to detect differences in causal factors of these spills.

The data-processing anomaly possibility was investigated by selecting a typical Texas county and determining its failure rate. Austin County was selected. Austin County had nine oil spills from 1973 through 1975 on its 154.4 miles of pipeline. The Austin County failure rate of 19.4 is midway between the reservoir rate and the Texas rate. In Austin County, as over the reservoir, there was a tendency for most pipeline failures to be reported by several pipeline companies for some lines, and no failures to be reported for other pipelines. Thus, the individual pipeline failure rates may be related to the age, method of construction, or degree of maintenance of the pipelines in a given geographical area. However, an assessment of reasons for the differences in failure rates, especially over the Edwards Underground Reservoir, was beyond the scope of this project.

In calculating the probabilities needed to accomplish objectives 2 and 3, it is necessary to choose an anticipated oil spill failure rate for the EUR over the next 20 years. The discrepancy between the recent failure rates for the reservoir area and for the rest of Texas complicates this choice. Our approach is to perform the calculations for both of two cases. The first case, which pessimistically assumes the 1975 failure rate for all of Texas (λ_{TX} = 49.79 spills per thousand miles per year), is a realistic failure rate projection for the Edwards Underground Reservoir in the future. The second case optimistically assumes the 1970 to 1975 reported failure rate for the Edwards Underground Reservoir (λ_{EUR} = 6.334 spills per thousand miles per year) will continue in the future.

F. Likelihood of a Hydrocarbon Spill Over the Edwards Underground Reservoir

The probability that one or more pipeline-related hydrocarbon spills will occur over the Edwards Underground Reservoir over various time periods can be computed from a variation of the Poisson model Equation (1). The probability of one or more spills is

$$1 - P(K = 0) = 1 - e^{-\lambda t}.$$

Assuming that all the existing 236.8 miles of pipeline, and only this pipeline, will be in use over the reservoir in the foreseeable future, the probability of one or more spills was computed for time periods of 1, 2, 3, 5, and 10 years. The calculations were performed both for the recent Texas failure rate case (λ = 49.79) and for the recent reservoir failure rate case (λ = 6.33). The results are presented in Table 8. With the Texas failure rate assumption, Table 8 indicates there is a near certainty of at least one hydrocarbon spill over the reservoir each year. With the recent reservoir failure rate assumption, there is a 77-percent chance of one or more spills in a year, a 95-percent chance in 2 years, a 99-percent chance over 3 years, and over a 99.9-percent chance in a 5-year period. Thus, it is very likely that one or more hydrocarbon spills will continue to occur over the Edwards Underground Reservoir in most years.

TABLE 8. ESTIMATED PROBABILITY THAT ONE OR MORE PIPELINE-RELATED SPILLS WILL OCCUR OVER THE EDWARDS UNDERGROUND RESERVOIR USING A POISSON FAILURE MODEL

Length of Time, Years	Probability of One or More Spills	
	Based on 1975 Texas Failure Rate (λ=49.79)	Based on 1970 - 1975 Edwards Reservoir Failure Rate (λ=6.33)
1	0.999998	0.7769
2	0.99999999994	0.9502
3	--	0.9889
5	--	0.9994
10	--	0.999997

G. Estimated Size of the Largest Potential Hydrocarbon Spill Over the Edwards Underground Reservoir

In the Trans-Alaska Pipeline Environmental Impact Statement[14], a procedure involving the distribution of maximum drainage volumes was used to estimate the exposure to maximum potential amount of drainage. This technique makes the following assumptions:

(1) All lines are full and are not flowing.
(2) Pumps have shut down and all valves are closed.
(3) A complete separation of the line immediately upstream of a valve and the line drains completely.

The procedure involves calculating the length and volume between valves. The following table presents the results of applying this analysis to the EUR.

Distribution of Maximum Drainage Volume

Maximum Potential Amount of Drainage (Barrels) Following Shutdown	Exposure to Maximum Potential Amount of Drainage	
	Percent	Miles
0-500	0.3	0.7
500-1000	0.8	2
1000-5000	12.2	30
5000-10000	42.2	104
10000-15000	12.5	31
15000-20000	15.5	38
20000-25000	16.3	40

This information suggests that there is a potential for large volumes of oil to spill if a line should separate or be penetrated. The probabilities for such spills are presented in the following section.

An important factor in the likelihood of contamination of the Edwards Aquifer is the size of the largest hydrocarbon spill over it. The probability that the largest pipeline-related spill over the reservoir over a specified time period will be in a certain range of gross losses can be computed from Equation (9). The calculation procedure is

$$P(\nu_1 < V_{max} \leqslant \nu_2) = P(V_{max} \leqslant \nu_2) - P(V_{max} \leqslant \nu_1).$$

Assuming there continues to be 236.8 miles of pipeline over the Edwards Underground Reservoir, these probabilities were computed for time periods of 1, 2, 3, 4, 5, 10, 15, and 20 years and for gross loss intervals of 0-99, 100-249, 250-499, 500-999, 1000-4999, 5000-9999, 10000-14999, 15000-19999, and 20000+ barrels. Again two cases were considered: the pessimistic case using the $\lambda = 49.79$ reported failure rate for Texas in 1975, and the optimistic case using the $\lambda = 6.33$ reported failure rate over the reservoir from 1970 through 1975. The probabilities calculated for both cases are shown in Table 9.

If the $\lambda = 49.79$ Texas failure rate occurs over the reservoir in the future, Table 9 shows that the largest spill over the reservoir is likely (has about a 61-percent probability) to be between 100 and 499 barrels for a 1-year period. As the length of time increases, the size of the largest anticipated spill in this time period also increases. In a 2-year period, the largest spill is likely (66-percent probability) to have a gross loss between 250 and 999 barrels. Over time periods of 10 years or longer, the largest spill over the reservoir is very likely to exceed 1000 barrels. However, even for a 1-year time period, there is more than an 11-percent probability that the largest spill will exceed 1000 barrels.

For case 2, if the rate of pipeline failures over the reservoir remains at the 1970 to 1975 rate of $\lambda = 6.33$ failures per thousand pipeline miles per year, the largest anticipated spill is smaller than for

TABLE 9. ESTIMATED PROBABILITY THAT THE LARGEST PIPELINE-RELATED SPILL OVER THE EDWARDS UNDERGROUND RESERVOIR IN A SPECIFIED TIME PERIOD IS IN THE SPECIFIED VOLUME LOSS INTERVALS

Case 1. Based on the 1975 Texas Failure Rate
λ = 49.79 failures per thousand pipeline mile-years

Loss Interval, Bbls.	One Year Period	Two Year Period	Three Year Period	Four Year Period	Five Year Period	Ten Year Period	Fifteen Year Period	Twenty Year Period
0-99	0.0555	0.0031	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
100-249	0.2828	0.1114	0.0385	0.0131	0.0044	<0.0001	<0.0001	<0.0001
250-499	0.3240	0.3242	0.2517	0.1793	0.1230	0.0162	0.0021	0.0003
500-999	0.2174	0.3352	0.3902	0.4064	0.3993	0.2612	0.1441	0.0767
1,000-4,999	0.1166	0.2187	0.3081	0.3863	0.4547	0.6857	0.7990	0.8506
5,000-9,999	0.0032	0.0063	0.0095	0.0126	0.0158	0.0312	0.0463	0.0610
10,000-14,999	0.0004	0.0008	0.0012	0.0016	0.0020	0.0040	0.0060	0.0080
15,000-19,999	0.0001	0.0002	0.0003	0.0004	0.0005	0.0010	0.0015	0.0020
20,000+	<0.0001	0.0001	0.0002	0.0002	0.0003	0.0005	0.0008	0.0012

Case 2. Based on the 1970–1975 Edwards Reservoir Failure Rate,
λ = 6.33 failures per thousand pipeline mile-years

Loss Interval, Bbls.	One Year Period	Two Year Period	Three Year Period	Four Year Period	Five Year Period	Ten Year Period	Fifteen Year Period	Twenty Year Period
0-99	0.6923	0.4792	0.3318	0.2297	0.1590	0.0253	0.0040	0.0006
100-249	0.1789	0.2798	0.3295	0.3464	0.3429	0.2266	0.1224	0.0628
250-499	0.0777	0.1415	0.1932	0.2348	0.2676	0.3401	0.3291	0.2870
500-999	0.0349	0.0674	0.0978	0.1260	0.1523	0.2575	0.3275	0.3712
1000-4999	0.0157	0.0311	0.0463	0.0613	0.0759	0.1457	0.2099	0.2688
5000-9999	0.0004	0.0008	0.0012	0.0016	0.0020	0.0040	0.0061	0.0081
10,000-14,999	<0.0001	0.0001	0.0002	0.0002	0.0003	0.0005	0.0008	0.0010
15,000-19,999	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	0.0002	0.0003
20,000+	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	0.0001	0.0002

case 1. For a 1-year period, the largest spill is expected to be less than 100 barrels (69-percent probability); this includes the possibility of no spills during the year. There is less than a 2-percent chance of a spill exceeding 1000 barrels in any 1-year period. The likely range of the largest anticipated spill increases from under 250 barrels (with a 66-percent probability) for a 3-year period, to between 100 and 499 barrels (with a 61-percent probability) for a 5-year period, and to between 250 and 999 barrels (with 66-percent probability) for a 15-year period.

In terms of spills exceeding 1000 barrels, Table 9 suggests that if case 1 is realistic, there is high probability of such a spill occurring over the reservoir for time periods of several years or longer. If case 2 is realistic, the danger of such large spills is not too great for time periods of less than 10 years. However, even with the optimistic case 2, and for time frames as short as several years, the possibility of hydrocarbon spills exceeding 1000 barrels cannot be lightly dismissed.

H. Estimated Total Cumulative Amount of Hydrocarbons Likely to Be Spilled Over the Reservoir

Another factor, which may represent an even better measure of potential aquifer contamination than the largest spill, is the cumulative gross loss of hydrocarbons from all the spills likely to occur over the reservoir in a specified time interval. The cumulative hydrocarbon loss is calculated as the difference of two applications of Equation (6);

$$P(z_1 < Z \leqslant z_2) = P(Z \leqslant z_2) - P(Z \leqslant z_1)$$

This calculation was conducted over consecutive gross loss intervals (z_1, z_2) for appropriate time periods. The results are presented in Table 10, both for the pessimistic case 1 ($\lambda = 49.79$) and for the optimistic case 2 ($\lambda = 6.33$).

If case 1 is applicable for the Edwards Underground Reservoir in the future, Table 10 indicates there is only a 1.8-percent chance that the total amount spilled over the reservoir in 1 year will be less than 500 barrels. For this 1-year period, there is a 53.7-percent chance that the total gross loss will be between 1001 and 2000 barrels, and a 93.5-percent chance that this loss will lie between 501 and 3000 barrels. As Table 9 shows, these likely cumulative loss intervals increase in a nearly proportional manner with the duration of the time period. Over 3 years, for case 1, there is a 59-percent probability that the cumulative gross loss from all reservoir spills will be between 4001 and 6000 barrels, and a 94-percent probability that the total loss will fall between 3001 and 7500 barrels. Over a 5-year time period, the cumulative loss ranges continue to mount : a 47-percent chance for between 7001 and 9000 total barrels of gross loss, and a 97.4-percent probability of losing between 5001 and 12,000 barrels. If the Edwards Underground Reservoir should in the future experience the same rate and size of pipeline failures that were reported for the entire State of Texas in 1975, the cumulative hydrocarbon gross loss over any 5-year period would almost always exceed 3000 barrels; 9000 barrels of gross loss could usually be expected over the 5 years.

If the reservoir should continue to experience the same failure rate as for the spills reported from 1970 to 1975 (case 2), the gross volume spilled will be much lower than for case 1. Including the possibility of no spill, there is a 52-percent probability that cumulative gross loss in 1 year will be 100 barrels or less, and a 96-percent probability of less than 800 barrels of cumulative loss. Over a 5-year interval with case 2, there is a 65-percent chance of having a cumulative loss between 401 and 1400

TABLE 10. ESTIMATED PROBABILITY THAT THE CUMULATIVE VOLUME OF THE GROSS LOSS IN PIPELINE-RELATED SPILLS OVER THE EDWARDS UNDERGROUND RESERVOIR WILL BE IN THE SPECIFIED LOSS INTERVALS

Case 1. Based on the 1975 Texas Failure Rate
λ = 49.79 failures per thousand pipeline mile-years

Loss Interval, Bbls.	Probability of Cumulative Gross Loss Volume in Interval		
	One Year Period	Three Year Period	Five Year Period
0-500	.01849		
501-1000	.13578	<.00001	
1001-1500	.26881	.00008	
1501-2000	.26939	.00097	<.00001
2001-2500	.17573	.00590	
2501-3000	.08480	.02165	.00001
3001-3500	.03263	.05392	
3501-4000	.01051	.09885	.00038
4001-4500	.00293	.14107	
4501-5000	.00072	.16327	.00599
5001-5500	.00016	.15806	
5501-6000	.00003	.13111	.03824
6001-6500	.00001	.09499	
6501-7000	<.00001	.06104	.12102
7001-7500		.03524	
7501-8000		.01847	.21878
8001-8500		.00887	
8501-9000		.00393	.24967
9001-9500		.00162	
9501-10,000		.00062	.19356
10,001-11,000			.10782
11,001-12,000			.04509
12,001-13,000			.01466
13,001-14,000			.00381
14,001-15,000			.00081
15,001-16,000			.00014
16,001-17,000			.00002
17,000-18,000			<.00001

TABLE 10. ESTIMATED PROBABILITY THAT THE CUMULATIVE VOLUME OF THE GROSS LOSS IN PIPELINE-RELATED SPILLS OVER THE EDWARDS UNDERGROUND RESERVOIR WILL BE IN THE SPECIFIED LOSS INTERVALS (Cont'd)

Case 2. Based on the 1970-1975 Edwards Reservoir Failure Rate,
λ = 6.33 failures per thousand pipeline mile-years

Loss Interval, Bbls.	Probability of Cumulative Gross Loss Volume in Interval			
	One Year Period	Two Year Period	Three Year Period	Five Year Period
0-100	0.5196	0.2059		
101-200	0.1230	0.1129	0.1408	0.0227
201-300	0.0967	0.1180		
301-400	0.0759	0.1126	0.1847	0.0655
401-500	0.0567	0.0996		
501-600	0.0407	0.0836	0.1960	0.1123
601-700	0.0283	0.0674		
701-800	0.0194	0.0528	0.1652	0.1423
801-900	0.0131	0.0404		
901-1000	0.0087	0.0302	0.1211	0.1492
1001-1100	0.0058	0.0223		
1101-1200	0.0038	0.0162	0.0803	0.1368
1201-1300	0.0025	0.0116		
1301-1400	0.0017	0.0082	0.0497	0.1134
1401-1500	0.0010	0.0057		
1501-1600	0.0007	0.0040	0.0289	0.0867
1601-1700	0.0005	0.0028		
1701-1800	0.0003	0.0019	0.0160	0.0621
1801-1900	0.0002	0.0013		
1901-2000	0.0001	0.0009	0.0085	0.0420
2001-2200			0.0045	0.0272
2201-2400			0.0022	0.0169
2401-2600			0.0011	0.0101
2601-2800			0.0005	0.0059
2801-3000			0.0002	0.0033
3001-3200			0.0001	0.0018
3201-3400			<0.0001	0.0010
3401-3600				0.0005
3601-3800				0.0003
3801-4000				0.0001

TABLE 10. ESTIMATED PROBABILITY THAT THE CUMULATIVE VOLUME OF THE GROSS LOSS IN PIPELINE-RELATED SPILLS OVER THE EDWARDS UNDERGROUND RESERVOIR WILL BE IN THE SPECIFIED LOSS INTERVALS (Cont'd)

Case 2. Based on the 1970-1975 Edwards Reservoir Failure Rate,
λ = 6.33 failures per thousand pipeline mile-years

Loss Interval, Bbls.	Probability of Cumulative Gross Loss Volume in Interval	
	10 Year Period	20 Year Period
0-500	0.0033	
501-1000	0.0465	<0.0001
1001-1500	0.1559	0.0009
1501-2000	0.2450	0.0071
2001-2500	0.2378	0.0286
2501-3000	0.1644	0.0721
3001-3500	0.0880	0.1270
3501-4000	0.0385	0.1686
4001-4500	0.0143	0.1777
4501-5000	0.0046	0.1543
5001-5500	0.0013	0.1137
5501-6000	0.0003	0.0726
6001-6500	<0.0001	0.0410
6501-7000		0.0207
7001-7500		0.0095
7501-8000		0.0040
8001-8500		0.0015
8501-9000		0.0005
9001-9500		0.0002
9501-10,000		<0.0001

barrels, and a 95-percent chance of losing between 201 and 2400 barrels. In 20 years, the cumulative gross loss would be expected to be about 4300 barrels; the probability would be 93-percent of losing between 2501 and 6500 barrels. Assuming that the EUR leak rate remains at its recent value, not considering the apparent trend in decreasing leak numbers, a sizable volume of crude oil is likely to be spilled over the Edwards Underground Reservoir over a 20-year period.

VII. PREDICTIONS OF IMPACTS OF PIPELINE LEAKS

A. Selection of Cases

The purpose of this section is to provide general observations concerning possible impacts of pipeline leaks in the Edwards Aquifer drainage basin and source zone. These predicted impacts were made considering the probability of occurrence of such leaks. Leaks have occurred in the area with no observable impairment of water quality.

The impact of two sizes of leaks were considered in this section–small (0 to 100 barrels) and large (> 10,000 barrels). These leak sizes were selected because leaks of 0 to 100 barrels have a reasonably high probability of occurrence in any given year and because approximately 44 percent of the length of the pipelines have an exposure to the maximum potential amount of drainage (in excess of 1000 barrels). The large leaks are considered in the discussion of impacts even though the probability of occurrence was determined to be negligible (~ 0.001 for each time period considered). The consideration of these ranges will provide insight into possible impacts of leaks of any size, including the range of 100 to 10,000 barrels.

This area in which a leak could occur is important in the determination of potential impact. For the purpose of this presentation, the drainage basin (or source zone) was divided into two general areas–stream crossings (including the recharge zone) and nonstream crossing areas. The non-crossing areas are those locations within the drainage basin which do not involve major, identifiable stream bed crossings. It is recognized that any area within the source zone of the Edwards Reservoir is within the drainage basin of some stream contributing to recharge, but for evaluation of potential effects of oil leaks, only two types of area were considered.

Two flow conditions were considered in the stream-crossing areas: flowing streams and intermittent streams. The Blanco River was considered as the primary example of flowing streams while such streams as Hondo Creek and Verde Creek were considered examples of intermittent streams.

Types of spills, areas, and flow conditions were examined in the following combinations in a ranking of estimated probability of occurrence:

(1) Small leak in nonstream area
(2) Small leak in intermittent stream
(3) Small leak in flowing stream
(4) Large leak in nonstream area
(5) Large leak in intermittent stream
(6) Large leak in flowing stream.

B. Potential Impacts

The impacts examined in this section deal primarily with potential contamination of recharge water. An examination and prediction of the consequences of oil in the artesian portion of the reservoir are beyond the scope of this report. An evaluation of after-the-fact data would require documentation of the effects of oil contamination for each recharge stream, the sorption characteristics of various portions of the aquifer, and potential points of withdrawal of the contaminated water. The lack of such information precludes the evaluation of the impact of leaks after they reach underground water.

The following prediction of impact of leaks is based upon discussion of the six scenarios listed above. The analysis of these situations could serve as a representation of potential impacts.

- **Small Leak in Nonstream Area**

This particular situation is likely to be the most probable type of leak occurrence because the 0- to 100-barrels leak has the highest probability of occurrence and because the majority of the pipelines are in nonstream areas (65 percent). The leak would likely be the result of external corrosion with a resulting low flow rate. The leak would likely be discovered by observation of damaged vegetation along the pipeline right-of-way (row) observed by air over-flight or local residents. The damaged vegetation might extend some 100 feet along the row and 30 feet out from the pipeline. The leaking oil would be contained in the topsoil and the backfill material of the pipeline.

The oil spill countermeasures[5] are:

(1) Stop the leak and contain the spill,
(2) remove the spilled oil and dispose of it,
(3) and restore the environment.

If step 1 was the only countermeasure taken, the impact of a leak of this size would be negligible. Some minute amounts of oil might go into precipitation run off but would not likely be significant at the point of recharge due to dilution in the streams. By taking steps 2 and 3, the effects of the leak would be further mitigated.

- **Small Leak in Intermittent Stream**

The impact of a leak of this type depends to a large extent on the proximity of the leak to the direct recharge area of the stream and whether or not the stream is flowing at the time of the leak. If a leak should occur when the stream is not flowing and is at a distance from the recharge zone, the impact of the leak would be similar to that of a leak in a nonstream area if all oil spill countermeasures were carried out. The pipelines are buried and a small leak due to external corrosion would not flow directly into a stream, but would saturate surrounding soil and backfill material until a sufficient volume was leaked to cause discharge of the material. Oily material might enter the stream by going into solution when the stream was flowing. By removing the majority of the oil-contaminated overburden, the impact of such a leak would be substantially mitigated. Dilution of the oil would also tend to reduce the impact of a leak of this type during periods of stream flow.

- **Small Leak in Flowing Stream**

A small leak in a flowing stream (such as the Blanco River) represents an anomalous situation. The rate of flow of the leak would probably determine the rapidity with which the leak would be discovered and, therefore, its impact. The "slow" leak might produce only a "sheen" on the water surface, resulting in an extended time before discovery of the leak. This situation would result in low concentrations of oil, but would be extended over a longer time period.

The "faster" leak might produce visible quantities of oil in the water, resulting in a more rapid discovery, especially in the case of the Blanco River which is used extensively as a recreational area. The larger concentrations of oil are more amenable to recovery operations such as oil booms, hay barriers, etc. The length of pipeline crossing the Blanco River represents approximately 2 percent of the total aquifer pipeline miles. Assuming the random nature of pipeline leaks and the low overall rate of leaks within the Edwards area, the probability of such a leak is low. Assuming an average discharge of 139 cfs for the Blanco River[3] and 100 barrels (4200 gallons) leaked in one day, and assuming the oil was mixed with the water at the leak site, the resulting concentration would be on the order of 40 mg/ℓ in a segment of the river (disregarding dispersal or losses due to volatization or adsorption). This concentration represents a moderately severe impact with respect to the quality of drinking water supplies withdrawn directly from the river. The immediate effect would be short-lived and would be washed from the system within a short time period.

The long-term effect of a loss of this type on the underground water would be more difficult to estimate. If cleanup operations were sufficiently responsive, minimal amounts of oil would enter the underground supply. If cleanup efforts were not successful or not conducted, some oil would likely enter the underground water.

- Large Leaks

The prediction of impact of large leaks will be considered in general terms without being overly specific regarding location or area of the leak. Most large leaks are the result of interference of human origin.[19] This observation was confirmed by our review of the TRC data. Frequently, earth-moving equipment that caused the pipeline failure can be used to initiate spill control countermeasures by constructing earth dams as holding basins. In the case of the large leaks, line pressure drops will cause the automatic shutoff of pumps and closure of valves.

The likely impact of a large leak in nonstream areas on stream water quality and resulting underground water quality is minimal because of the physical distance from the streams.

The impact of a large leak on an intermittent or flowing stream is likely to be severe. Due to the low probability, the occurrence of such a spill is unlikely; however, immediate spill control countermeasures would mitigate the severity of the leak if response was rapid and appropriate. The fact that oil floats on water is also significant. As long as any moving water is present at the recharge point, the water would tend to hold the oil up out of the aquifer and transport it beyond the recharge area. The greatest chance for oil penetration might be in an intermittent- or low-flowing stream.

VIII. PIPELINE CONSTRUCTION–A REVIEW OF CURRENT SPECIFICATIONS

A. Introduction

Section VII 4 (9) of the Texas Water Quality Board Order No. 75-0128-20, commonly called the Edwards Order, requires that:

> Hydrocarbon transmission lines will be constructed in accordance with Board specifications in the absence of specifications of some other State or Federal agency having the jurisdiction to so regulate. Board specifications will be based solely on the protection of the Edwards Underground Reservoir.

To date, the Board has not established its own specifications. In fact, Texas has no agency with specific construction specifications for liquid-carrying pipelines. The Texas Railroad Commission has regulations requiring operators of liquid pipelines to obtain an operating permit. But this permit does not require construction to be according to TRC specifications. Apparently, there is no current effort underway to establish such requirements either by the Board or the TRC.

B. Current Regulations

At the present time, the only regulations requiring liquid pipeline carriers in Texas to construct according to certain specifications are the regulations of the U.S. Department of Transportation (DOT) published as 49CFR195 titled "Transportation of Liquids by Pipeline." The regulations only apply to the transportation by pipeline in interstate and foreign commerce of hazardous materials, petroleum, and petroleum products. Excluded products are water and gases. Gathering pipeline systems are also excluded.

The Part 195 DOT regulations include requirements for accident reporting, design, construction, hydrostatic testing, and operation and maintenance. Spills of 50 or more barrels of liquid must be reported. Details of such losses must be provided on DOT Form 7000-1. Minimum design requirements apply to new steel pipeline systems and for relocation, replacement, or changing existing steel pipe systems. Design parameters included for general consideration are temperature, internal and external pressures, external loading, valve identification, closures, and flanged connections. Construction requirements cover placement and material inspection; pipe bending; welding; external corrosion protection; cathodic protection; valve location; pumping equipment; and record keeping. For example, minimum depths of cover over buried lines are specified for systems location in various locations such as residential areas or stream crossings. Valves are required to provide the capability to isolate stream crossings, pump stations, tank farms, and potable reservoir crossings.

Each pipeline system covered by the above requirements must be hydrostatically tested without leakage in accordance with specific requirements. The test pressure for each test must be maintained for at least 24 hours using only certain approved testing mediums. Records of the details of each test must be maintained for as long as the tested facility is used.

Operation and maintenance requirements include maintenance of maps and records for each system, restrictions on operating pressures, line marker requirements, inspection of crossings under navigable waterways, cathodic protection, testing for external and internal corrosion, valve maintenance schedules, overpressure safety devices, signs, and security provisions.

Numerous standards and specifications have been incorporated into these regulations by reference. Included are standards and specifications for construction, materials, and maintenance established by various associations. These associations include the American Petroleum Institute (API); the American Society of Mechanical Engineers (ASTM); the Manufacturers Standardization Society of the Valve and Fittings Industry (MSS); and the American National Standards Institute (ANSI). The various standards and specifications cover valves, welds, pipes, and fittings.

Although the Part 195 regulations only apply to interstate or foreign commerce of hazardous materials, the DOT has statutory power under the Transportation Safety Act of 1974 (PL93-633) to promulgate similar regulations to control intrastate commerce of hazardous materials. Thus, DOT has the power to control the construction of all liquid or gas commerce via pipeline. To date, regulations have not been written and promulgated under authority of this Act.

Information obtained from the four pipeline companies operating the pipelines crossing the recharge study area indicates all these lines are presently considered interstate pipelines. Therefore, those sections of the Part 195 regulations pertaining to pipeline operation and maintenance apply to these lines. However, since all four lines were originally built prior to 1969 when the Part 195 regulations were first promulgated, it is not known whether or not DOT construction specifications were followed during construction. It is known that all four lines are presently protected by cathodic protection systems, high- or low-pressure cutoff equipment, and strategic placement of valving. All these provisions are addressed in the Part 195 regulations.

Based upon the statistical analysis of the potential for a major pipeline failure and resulting hydrocarbon spill in the recharge study area, there does not appear to be an immediate need for more stringent construction, operation, and maintenance requirements for interstate pipelines. However, since there are no such requirements for intrastate lines, the potential does exist that an intrastate line could be built crossing the recharge area which would not meet the interstate regulations. Should this occur, the probability of a spill and subsequent damage to the aquifer would undoubtedly increase. In the event an intrastate pipeline was proposed for construction in the study area, it seems reasonable that the TWQB and the EUWD should have a means to ensure the provisions of the Board Order are adequately fulfilled.

A requirement for pipeline retrofit modifications on the lines in the study area does not appear justified. This is based on the following factors which have previously been discussed:

(1) All the pipelines in the study area are being operated, maintained, and inspected according to the DOT Part 195 regulations.

(2) The low frequency of leaks from the pipelines in the area compared to Texas as a whole would seem to indicate the construction methods used on these lines were adequate.

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